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September 1978

Electrified Bed Evaluation

by

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Contract No. 68-02-1487
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Prepared for

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ABSTRACT

The report gives results of an evaluation of a prototype electrified bed (EFB) particulate collection device. The 500 cfm unit, which utilizes mechanical and electrical mechanisms for collection, was installed at an asphalt roofing plant during the tests. Fractional efficiency was determined with upstream and downstream impactors. Total mass efficiency was determined with glass fiber filter sampling trains. The mean inlet loading was 0.2585 gr/dscf and the mean outlet loading was 0.0037 gr/dscf, for an average efficiency of 98.57 percent. The inlet aerosol has a mass median diameter of about 1 micrometer, with 90 percent less than 2 micrometers. Measurements of volatile hydrocarbons by on-site gas chromatography showed that the inlet concentration of approximately 100 ppm was reduced by 20 to 50 percent by the device.

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Filtration	Impactors	Pollution Control	07D	
Electrostatics	Glass Fibers	Electrified Beds	20C	11E, 11B
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Personnel of EFB in cooperation with the plant operators of Bird & Son provided the collection of plant operation data. Additional information regarding the EFB unit was provided by Mr. Peter Zieve of E.F.B. Inc., Woburn, Mass.

SECTION I

CONCLUSIONS

The results of six tests conducted on the EFB pilot control device indicate that the unit was an effective means of removing asphalt plant flue gas emissions. The results of combined upstream and downstream testing with impactors and total mass trains determined the efficiency of the unit to be greater than 98 percent for particles less than 2 micrometers diameter. It was determined that approximately 90 percent of the particles were less than 2 micrometers in the inlet stream. The mean inlet grain loading was determined as 0.2585 gr/dscf and the mean outlet loading was 0.0037 gr/dscf which results in an overall efficiency of 98.57 percent.

The results of the volatile hydrocarbon analyses of the flue gas showed that the inlet concentration of approximately 100 ppm was reduced up to 50 percent by the device.

While the results of these tests indicate a high efficiency of particulate removal, the tests cannot be applied to other types of emissions since the effect of the electrical and mechanical collecting mechanisms of the EFB unit is unknown for emissions other than those tested. It should be noted that the results of this testing program indicated a decreasing efficiency of particulate removal for the larger diameter particles. It is unknown if this is characteristic of the EFB unit or the result of abnormalities in the test results due to bed losses in the outlet stream. While this anomally had little effect on the results of this testing program, the problem may be significant in other applications.

SECTION II

RECOMMENDATIONS

It is recommended that further testing of a full scale operation be undertaken to fully evaluate the use of the EFB unit in applications larger than the pilot operation tested. A more extensive testing program such as described in "A Method for the Determination of Particulate and Total Gaseous Hydrocarbon Emissions From the Asphalt Roofing Industry"[1] would be required for a representative sampling of total emissions from a full scale operation. Since the effect of a full scale operation would change a number of critical variables related to the efficiency of the unit, it would be necessary to implement an inclusive testing program to fully evaluate the full scale operation of the EFB unit.

SECTION III

INTRODUCTION

BACKGROUND

The work performed in this report is the result of the testing of a pilot operation of a new control device for industrial emissions. The purpose of the testing was to evaluate the efficiency of removal of particulate and hydrocarbon emissions by the EFB* Inc. control device at the Bird and Son Asphalt Plant in Norwood, Mass. Testing was performed in a slip stream ducted from the asphalt saturator hood duct. The data reported is not applicable to emissions from the Bird and Son Plant but is used for the purpose of evaluating the efficiency of the EFB control device.

APPROACH

The efficiency of the EFB control device was determined by comparison of the inlet and outlet stream parameters. Particulate removal efficiency was determined as a function of total mass and particle size. Hydrocarbon content measurements from on-site analysis by gas chromatography were compared for the inlet and outlet streams to provide an indication of volatile organic reduction efficiencies. In addition, measurements of the physical parameters of the inlet and outlet flow streams were made for each test to provide necessary data for calculation of stream flow rates and required sampling rates.

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*EFB is a registered trademark of EFB Inc. Woburn, Mass.

A series of four preliminary tests was performed on 10/27, 11/2, 11/30, and 12/1 to provide information for the preparation of the test plan. These tests were designed to provide preliminary efficiency data and also to test the proposed sampling methods. Problems with plant production rate variability and also discrepancies in stream flow calculations were encountered and subsequently corrected. Test sampling rates and duration were adjusted to provide representative data for the major testing program.

The original plan for the major testing program was to consist of seven complete tests of the inlet and outlet streams with correlated plant production data. This plan was modified to provide only six tests due to excessive plant downtime on the last day. In addition, the original plan was to include the condensation nuclei counter in the testing. This was omitted due to a malfunction in the instrument. Other testing was as scheduled except for a reduced number of fixed inorganic gas analyses.

SECTION IV

PROCESS DESCRIPTION

The EFB control device was installed as a pilot demonstration unit at the Bird & Son Asphalt Plant in Norwood, Mass. The Bird & Son Plant manufactures asphalt-coated shingles, from which the fumes emitted from the shingle coating process are collected via overhead hoods and vented into the plant boiler (see Figure 1).

The EFB device is installed on a slipstream duct off the main duct. The slipstream flow is controlled by a hand-operated damper, but no means of monitoring the flow parameters is available.

This EFB control device consists of two beds of slate particles perpendicular to the flow of the gas stream. Between the two beds of slate is a corona charger (see Figure 1) which imparts an electrical charge to the gas stream in order to charge the incoming particulate. The filter beds are changed as needed from overhead hoppers (see Figure 2). The oil coated bed particles are removed from below and subsequently disposed or recycled. Beds were changed in half batches before or after testing but never during the testing schedule.

For the purposes of this testing, monitoring of production rate was done by recording the feet-per-minute rate of felt used in the shingle production. This data was collected by personnel from EFB and relayed to the GCA sampling team. Other data required for the testing such as the physical parameters of the gas stream were collected by GCA personnel prior to each test.

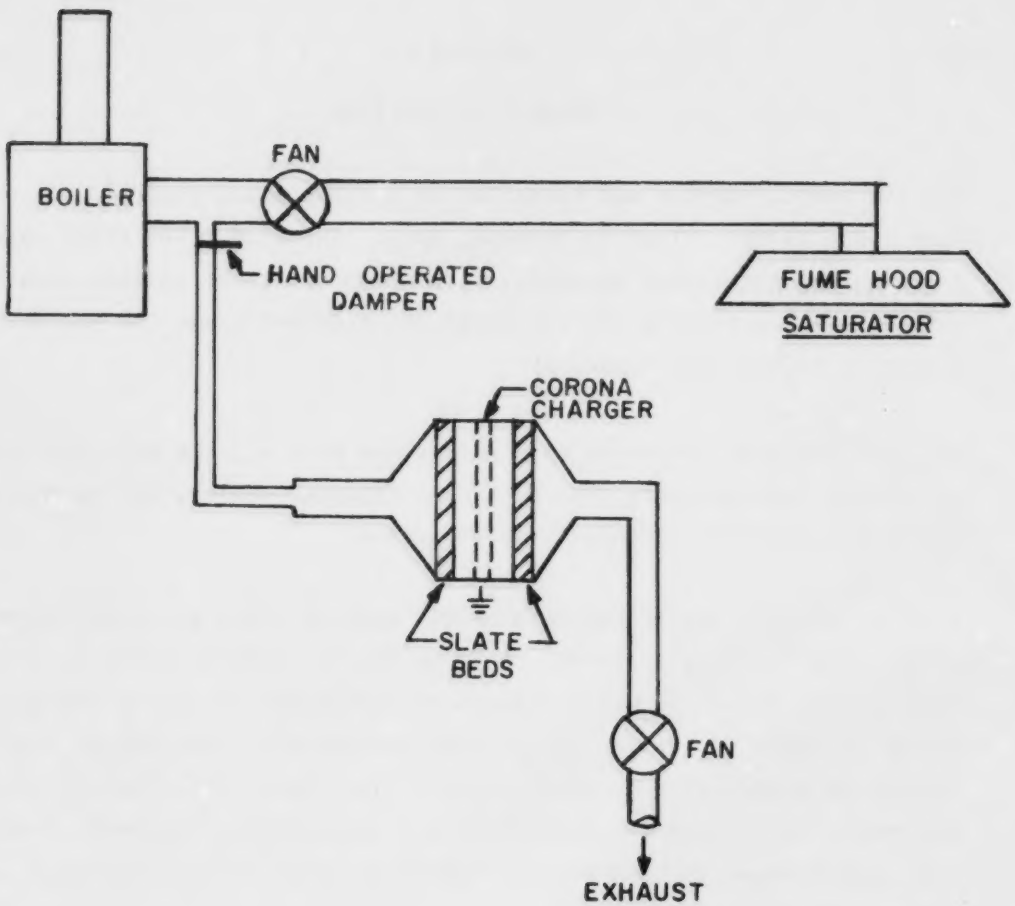

Figure 1. Schematic of EFB unit of Bird & Son, Norwood, Mass.

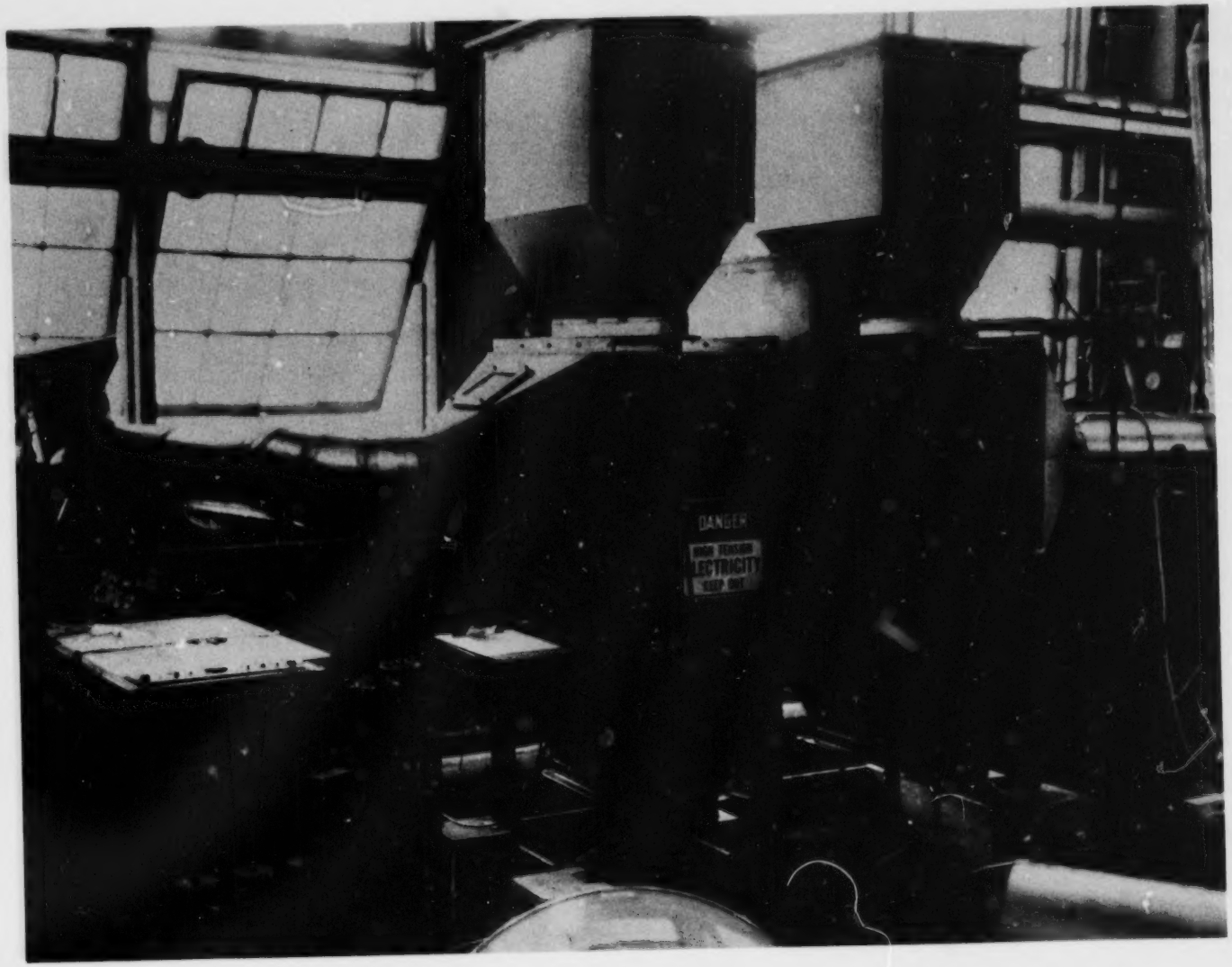

Figure 2. EFB plant operation at Bird & Son, Norwood, Mass.

While data was collected from the Bird & Son Plant, the results of this testing are not representative of any process emissions. The data collected was for the purpose of evaluating the efficiency of the EFB control device as a pilot demonstration unit.

SECTION V

EQUIPMENT AND METHODS

The EFB control device which was installed as a pilot demonstration unit at Bird & Son Co. was evaluated for the efficiency in removal of particulate and volatile organics from an asphalt fume stream. Total mass sample and fractional-sized samples were collected before and after the control device. In addition, samples of the particulate filtered gas were analyzed for volatile organics. The test program included four preliminary tests to evaluate the testing methods and to establish operating conditions. With the results of these tests, a series of six tests was designed to provide data for the evaluation of the EFB unit.

TESTING METHODS

Four tests were conducted on October 27, November 2, November 30, and December 1 on the EFB pilot unit at Bird & Son, Norwood, Mass. The purposes of these tests were to (1) establish typical operating conditions and parameters of the EFB unit; (2) to investigate the possibility of anomalous weight gains of the sampling train filters, and (3) to evaluate the testing methods.

Two types of sampling trains were used in the program. One train consisted of two 42 mm glass fiber filters connected in a series of stainless steel holders. The other train consisted of an Andersen 2000 impactor followed by a 42 mm glass fiber filter in a stainless steel filter holder (See Figure 3). Both types of trains included an air-tight vacuum pump, a dry gas meter with a calibrated orifice, and a cylinder of indicating silica

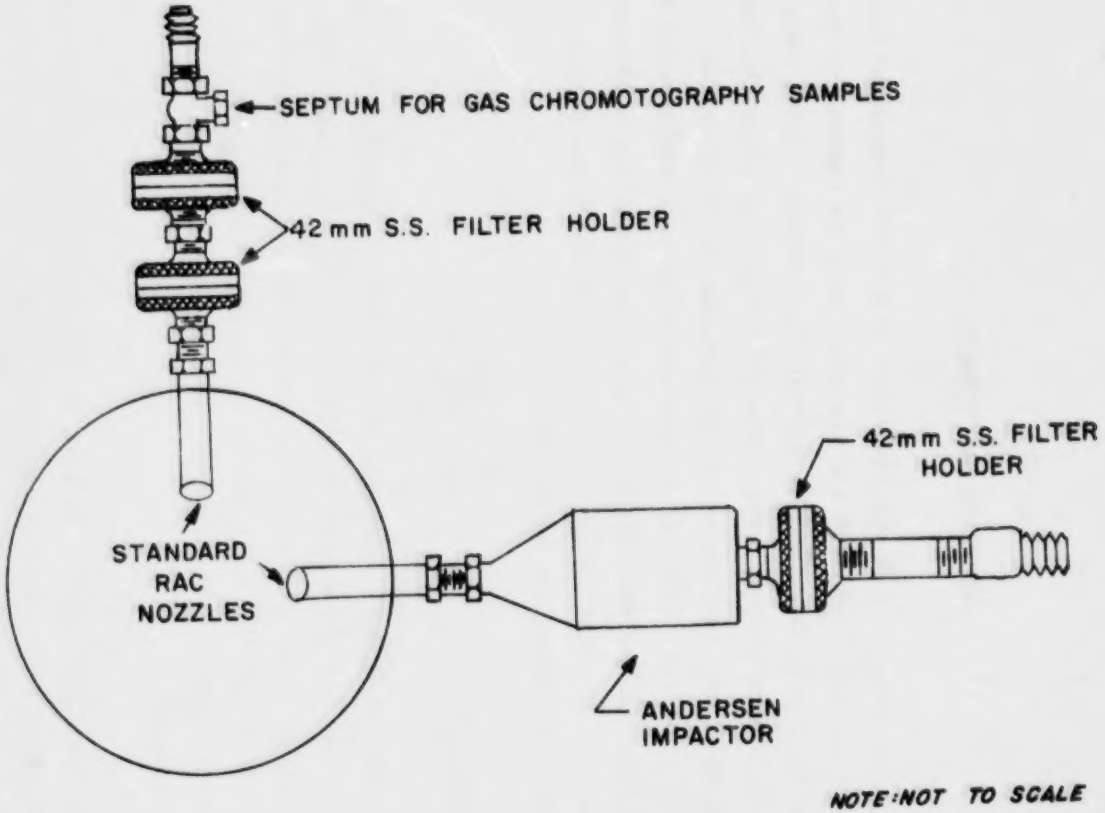

Figure 3. Placement and design of sampling trains for EFB control device evaluation

gel (see Figure 4). A pair of magnehelics were used to monitor the orifice pressure drop and static pressure.

The gas stream flow parameters were measured prior to each sampling with a standard 3-foot pitot tube and a micromanometer. Temperatures were recorded with an in-stack, metal stem, dial thermometer. Pitot readings were recorded for a total of 12 traverse points located according to Table 1.1 in Standards Methods of Performance for New Stationary Sources.[2] Due to the limited diameter and configuration of the ducting, it was necessary to locate sampling ports at the best available locations (as diagrammed in Figure 5). Results of pitot and temperature readings were used to calculate the inlet and outlet stream flow rates and also to calculate the required sample train nozzle sizes and sampling flow rates.

Sampling flow rates and times were such that impactor bounce would be minimized while acquiring a representative sample of the gas stream. Sampling time for the preliminary tests was between 90 and 180 minutes at a single point in each of the inlet and outlet streams. The gravimetric analyses of the train filters, substrates, and acetone washes were used to calculate total grain loadings and fractional size distribution of particles in the outlet and inlet streams. Efficiencies of particulate removal for the EFB device were derived by comparing these results for each test. Efficiency of removal of volatile organics was obtained by comparison of gas chromatography analysis of inlet and outlet gases. In addition, the inlet and outlet flue gases were analyzed by Orsat analyzer for fixed gas composition and the moisture content of the gas was determined gravimetrically from the silica gel cylinder in each train.

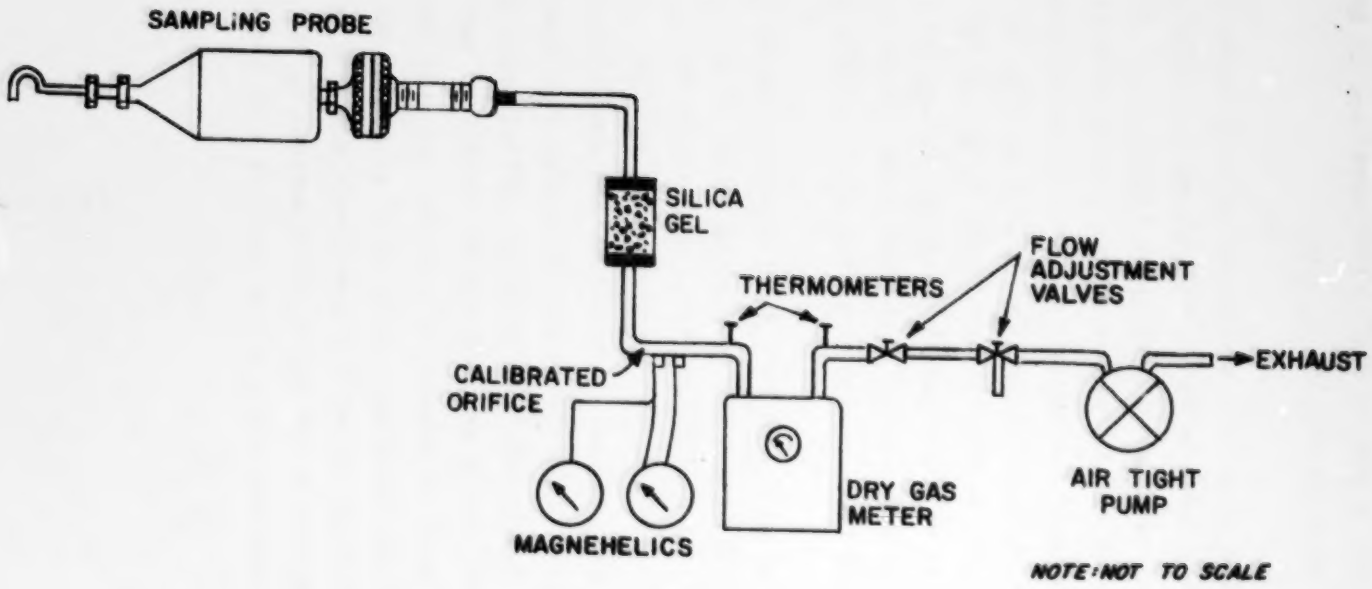

Figure 4. Sampling train schematic, EFB control device evaluation

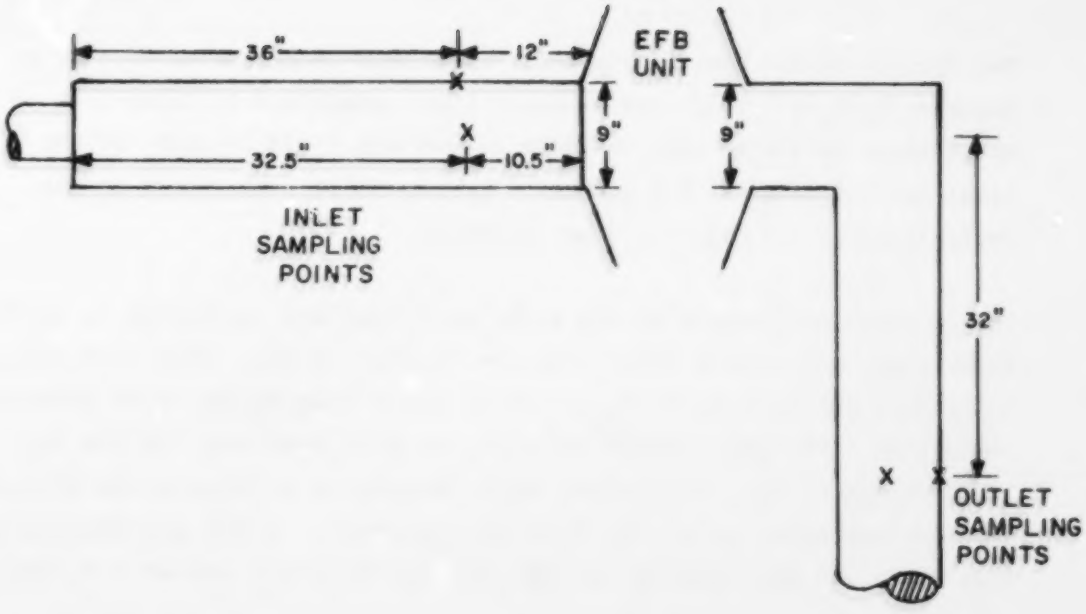

Figure 5. Location of sampling points on EFB control device

SECTION VI

RESULTS

PRELIMINARY RESULTS

The results of the preliminary tests which were conducted on October 27, November 2, November 30, and December 1 are summarized in Table 1. These tests indicated that the sampling methods could be used for the final testing program if a number of factors which contributed to the variability of the data could be minimized.

The problems encountered during these tests included variations in stack flow rates, and erratic fractional particulate catches. Flow rate variations were believed to be the result of the ducting design which produced nonuniform flows and resulted in erroneous pitot readings. At the recommendation of GCA, the ducting was redesigned to provide a more uniform and representative stream for velocity traverses. It was also suspected that there was some leakage through the unit which was corrected by EFB personnel.

The leakage in the system also contributed to the erratic fractional catches in the outlet stream. Particles caught in the outlet sampling trains were examined by microscopity and determined to be slate particles from the bed. This problem was remedied by EFB personnel prior to the major testing program.

The anticipated problem of anomalous weight gains by the filters was not encountered during this testing. The inlet filters did present a problem if the sampling time was such that the filters were saturated with liquid droplets. It was necessary to limit the inlet trains sampling

Table 1. RESULTS OF PRELIMINARY EFB TESTS

Test No.	Sample train	Inlet			Outlet			Efficiency (percent)
		T_{stk} (^{o}F)	Q_{stk} (acfm)	Grain loading (gr/dscf)	T_{stk} (^{o}F)	Q_{stk} (acfm)	Grain loading (gr/dscf)	
1	Impactors	-	-	-	112	204	0.0048	-
1	Filters	140	285	0.0379	112	204	0.0004	98.94
2	Impactors	145	243	0.2368	125	413	0.0134	94.34
2	Filters	145	243	0.2119	125	413	0.0281	86.74
3	Impactors	134	365	0.4105	107	540	0.0086	97.90
3	Filters	134	365	0.2604	107	540	0.0083	96.81
4	Impactors	140	439	0.1910	104	522	0.0164	91.41
4	Filters	140	439	0.1387	104	522	0.0125	90.27

time to 90 minutes or less in order to prevent loss of liquid droplets emissions from the filters.

Gas chromatography analyses of the inlet and outlet gas streams were included in preliminary Test No. 4. Gas samples were taken with a 5 ml gas tight syringe and analyzed for total volatile hydrocarbon and methane content. An AID Model 511 gas chromatograph with a 1 ml heated gas sampling loop and flame ionization detector was used for analysis. The results of Test No. 4 are reported in Table 2.

Table 2. FLUE GAS HYDROCARBON CONTENT, EFB TEST No. 4

Sample	Total hydrocarbon (ppmv)[a]	Methane (ppmv)[b]
Inlet	119.97	20.43
Outlet	83.40	11.47

[a] 3 ft s.s. open capillary.

[b] 6 ft × 1/8 in. s.s. porapak Q.

The results of this test indicated that the EFB unit was also capable of removing volatile hydrocarbon emissions and resultingly the testing method was included in the major test program.

One additional problem encountered during preliminary testing was the correlation of testing schedule to the production rate. This problem was remedied by the assistance of EFB personnel who agreed to check line speed-production rate at regular intervals during the testing of the EFB unit. This data was not available during the preliminary tests but was made available for the major testing program of tests 5 to 10 (See Appendix A.)

TEST RESULTS

On the basis of the information obtained during the preliminary testing, a test plan was developed to evaluate the efficiency of the EFB control device. A total of six tests were proposed which included total mass

emission analysis, fractional size distribution analysis and volatile organics analysis.

Testing took place from February 21 through February 24 with a total of six tests completed. Sampling included the total mass filter trains, Andersen Impactor trains, and gas chromatography analysis. In addition, velocity traverses were performed to obtain the necessary data to calculate the flue gas flow rates and the required sampling conditions.

Total Mass Testing - The results of the velocity traverses, gas chromatography analyses, and total particulate mass testing are included in Table 3. The efficiency of particulate removal was determined from the calculated grain loadings based on the gravimetric analysis of the filters and train washes from the total mass trains. The average efficiency for the six tests was 98.02 percent. If the low efficiency results of Test No. 5 are eliminated, the efficiency of total particulate removal was 98.56 percent and the resulting mean inlet grain loading is 0.2585 gr/dscf with a mean outlet grain loading of 0.0037 gr/dscf.*

It is unknown why the grain loadings of Test 5 are significantly higher than the other tests. It is possible that the lower efficiency of Test 5 was due to a longer run time of the total mass trains. The inlet filter appeared saturated and resultingly the efficiency may be lower due to sample loss. Tests of the inlet streams for Nos. 6 to 10 were run for shorter time periods to minimize this loss.

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*The basis for elimination is that for Tests 5 to 10 the standard deviation (θ) of the inlet was calculated as 0.03127 with a mean of 0.26719, and for the outlet θ was 0.00395 for a mean of 0.00528. The calculated grain loadings of Test 5 exceeded "1 θ" in both the inlet and outlet, with $P(z \geq 1.39) = 0.0823$ for the inlet and $P(z \geq 1.96) = 0.025$ for the outlet. $P(z \geq \frac{x - \mu}{\theta})$ is probability of occurrence.

Table 3. EFB TEST RESULTS

Test No.	Date	Sample location	Q (scfm)	T_{stk} (^{o}F)	Moisture[a] (percent)	Total hydrocarbon (ppmv)	Methane (ppmv)	Grain[a] loading (gr/dscf)	Particulate efficiency (percent)
5	2/21	Inlet	391.8	142	2.0	99	n.m.[b]	0.31061	95.81
		Outlet	416.6	113	1.6	87.1	14.1	0.01301	
6	2/22	Inlet	385.0	140	2.6	97.1	6.8	0.21779	98.20
		Outlet	445.9	111	2.1	78	4.5	0.00391	
7	2/22	Inlet	390.3	136	1.9	-	-	0.25002	98.76
		Outlet	454.1	103	1.7	-	-	0.0031	
8	2/23	Inlet	372.6	145	2.1	144	n.m.[b]	0.27630	99.15
		Outlet	471.7	113	1.6	73	n.m.[b]	0.00236	
9	2/23	Inlet	377.7	135	2.4	-	-	0.26693	98.66
		Outlet	472.4	111	1.8	-	-	0.00357	
10	2/24	Inlet	295.4	129	2.7	107	20.5	0.28151	97.97
		Outlet	374.0	104	1.9	56	14.3	0.00572	

[a]From total mass trains results.

[b]No measurement available.

Gas Chromatography Testing

Table 3 also includes the results of gas chromatography analyses of the flue gas for tests on each of the days. The results of these tests show that the inlet flue gas volatile hydrocarbon concentration was approximately 100 ppm and this was reduced by 20 to 50 percent by the EFB device.

With regard to this reported range in this efficiency, it should be noted that Test 8 and Test 10 used heating tapes around the outlet syringe sampling septum to equalize the temperature of the inlet and outlet sample streams. Temperatures of the gas streams were monitored and the heat tape output adjusted as necessary. This design was included to minimize the problem of organics condensing on the septum inner surface which could result in an abnormally-high total hydrocarbon value. Any differences in sample volumes between inlet and outlet would also be normalized by this modification. The reason for the variation in reported values for hydrocarbons is unknown but it would be likely to conclude that the 50 percent efficiency found in Tests 8 and 10 were more representative of the organic removal efficiency of the EFB device.

Fractional Size Testing

The results of the Andersen Impactor testing for fractional size distributions and efficiencies is available in tabular form in Appendix D and is presented graphically in Appendices B and C for each of Tests 5 through 10. Appendix C includes the differential size distribution curves for the inlet and outlet impactor tests. These graphs represent the relations between the particle mean geometric diameters and the differential mass distribution, dm/d Log D (dm/d log D = $\frac{\left(P_{I/100}\right) C_m}{\left(\log D_{s+1}\right)-(\log D_s)}$ where P_I is percent mass collected on stage s, C_m is total mass collected on stages, D_s is D_{50} for stage s).[3] From these graphs, the fractional efficiencies can be calculated for specific mean geometric diameters. Figure 6 represents the compilation of these calculations for 6 diameters of Tests 5 through 10.

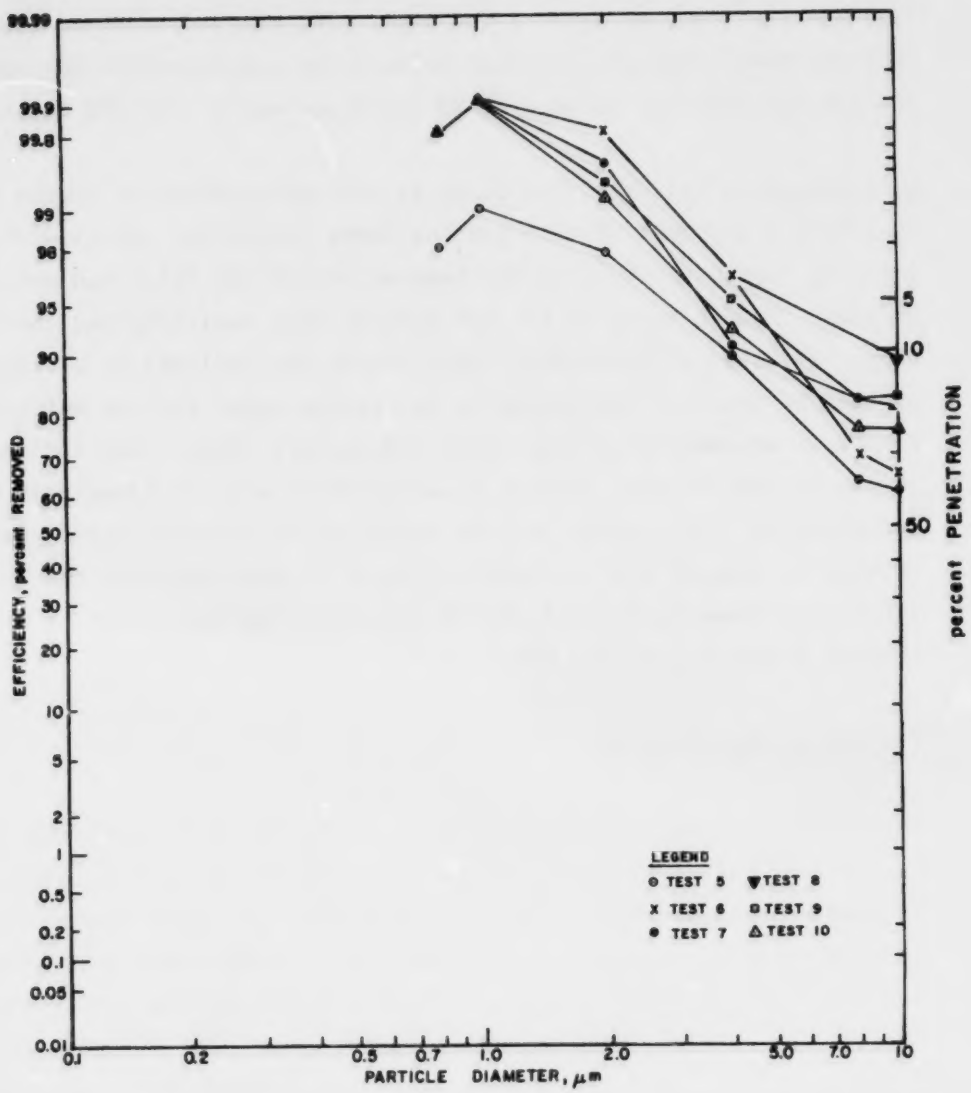

Figure 6. Fractional efficiencies of EFB unit as measured with Andersen impactor.

With the exception of Test 5, the results indicate an efficiency of greater than 99 percent for particles of approximately 1 μm mean geometric diameter. It is unknown why the efficiency decreases for the larger particle sizes. It is possible that the increase in outlet particle size distribution was the result of loss from the slate bed or from gaseous adsorption by the first stages in the impactor. Another possibility is that probe and expansion chamber wall losses may alter the values obtained for the larger particle sizes.[4] A third possibility is that particles in the device may coagulate due to either induced dipole moments or by kinimatic coagulation.[5]

Regardless of this anomaly, the overall distribution of the inlet aerosol was shown to consist of 50 percent of the particles with less than 2 micrometers mass median diameter. This information is presented graphically in Figure 7 for Tests 5 through 10. The data presented in Figure 7 was obtained from the graphs of particle size distribution included in Appendix B.

Figure 7 includes data from only the inlet streams. The graphs in Appendix B depict the outlet distributions with probe fractions included and excluded in the calculations.* This information is presented to demonstrate the problem in probe losses for the outlet stream sampling. The problem of probe losses is that the particulate collected is of unknown size distribution and cannot be included in fractional distributions. Probe losses can be minimized by the use of straight nozzles, but in sampling situations which do not permit this orientation the use of curved nozzles is acceptable.[6] For testing the EFB device, it was necessary to use the curved nozzles (RAC sampling train nozzles)

*See Appendix D for reported proble percent used in calculation.

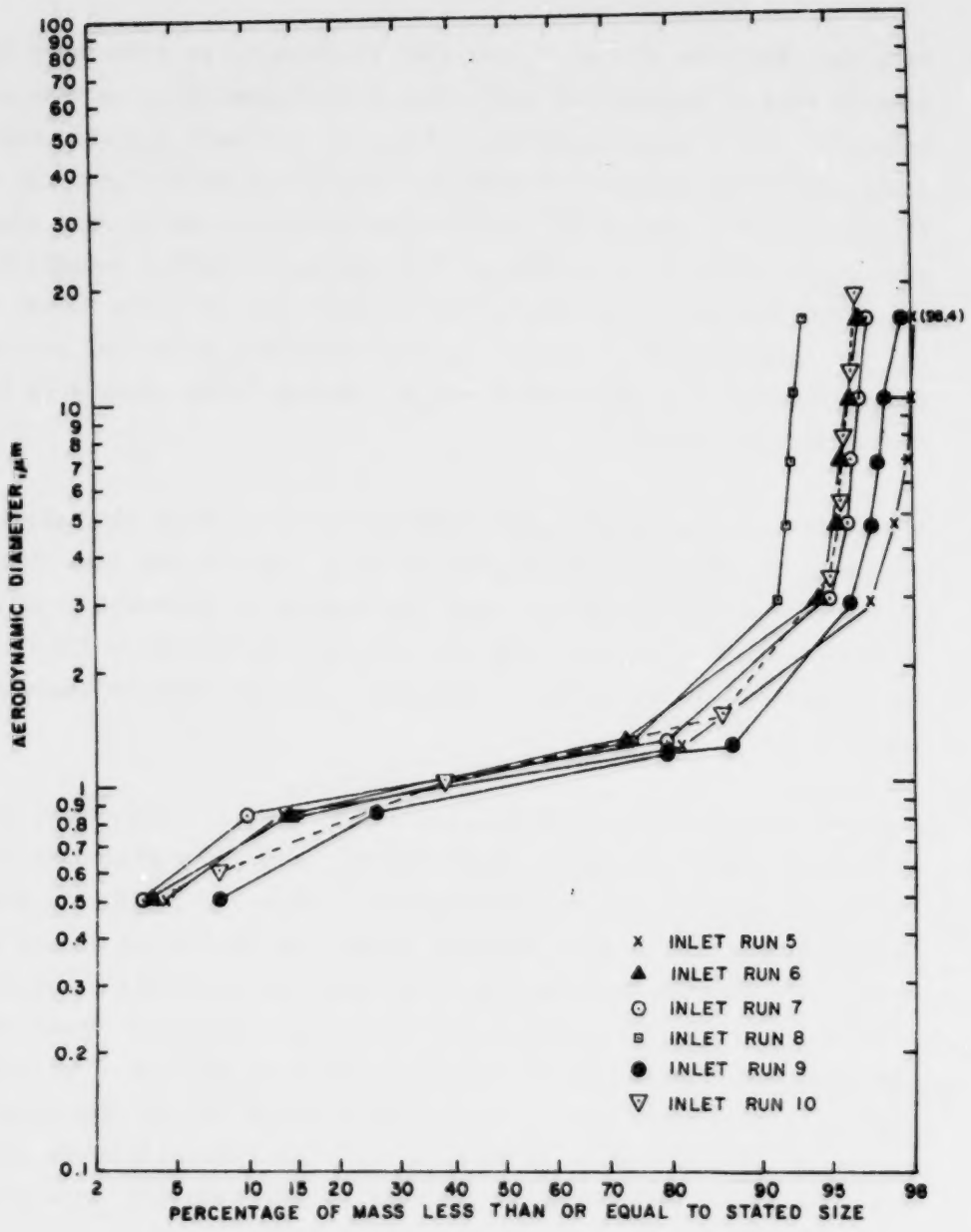

Figure 7. Fractional size distribution of EFB unit

due to the duct orientation and size. The use of these nozzles also permitted more accurate control of train flow rates and isokinetic sampling rates. The problem of probe losses was only appreciable in the outlet stream and not the inlet stream. It is possible that the electrical charge imparted by the EFB unit on the particles may affect the probe and wall losses of the impactor. Further testing would have been required to check this hypothesis.

The probe fractions and any wall adhering particles were presumably collected by the final rinses of the trains. The solvent frequently used for sampling train rinses is acetone.[7] In this testing program "Distilled in Glass" grade acetone was used for all tests. In addition, one test included a second wash of "DIG" methylene chloride as a check for the efficiency of the "acetone only" wash. The resulting gravimetric difference between acetone only and acetone plus methylene chloride washes amounted to 1.99 percent for the inlet stream and 0.4 percent for the outlet stream. These figures represent a minor degree of error resulting from use of acetone only as a train wash.

Other possible sources of error in testing would include the problem of weighing the oily filters and substrates which were sometimes obtained from the inlet testing. Filters or substrates which appeared oily were weighed on pre-tared, nonporous weighing papers. The possibility of volatile losses was a problem which was not investigated in this testing.

The possibility that the sample data obtained was not a representative sample should be considered since sampling was at a single point in the stream. This was necessary due to the duct size and configuration. Isokinetic sampling rate was maintained as close to ideal as possible to minimize any size discrimination. Impactor flow rates were also maintained around 0.4 acfm to minimize reentrainment of particles. Only in Test 5 was overloading of stages suspected as a problem. Tests 6 through 10 are considered as representative sampling for the pilot operation as tested.

Summary of Testing

The results of the six tests conducted on the EFB unit indicated that the control device was 98 percent or greater in the efficiency of removal of asphalt emissions of less than 2 μm aerodynamic diameter. The inlet aerosol had a mass median diameter of approximately 1 μm with 50 percent of the aerosol as less than 2 μm diameter. Volatile organics in the inlet flue gas were approximately 100 ppm with about 50 percent removal efficiency by the EFB device. The larger particles in the flue gas do not appear to be as efficiently removed, but the reason for this anomaly is unknown.

Our conclusion is that the EFB appears to be an effective means of collecting emissions from asphalt saturators. A conventional venturi scrubber would require at least 70 inches pressure drop to achieve similar efficiencies and would result in approximately eight times the operating costs of the EFB as tested.

REFERENCES

1. Riley, C. A Method for the Determination of Particulate and Total Gaseous Hydrocarbon Emissions from the Asphalt Roofing Industry. EPA Report, unpublished.

2. Standards of Performance for New Stationary Sources, Code of Federal Regulations, Method 1 of Appendix A, Part 60, Title 40.

3. Bradway, R.M. and R.W. Cass. Measurement Methods for Particle Size Distribution. Measurements in Process Streams. 1976.

4. Cushing, K.M., G.E. Lacry, J.D. McCain, and W.B. Smith. Particle Sizing Techniques for Control Device Evaluations: Cascade Impactor Calibrations. EPA-600/2-76-280. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

5. Dennis, R. (ed.). Handbook on Aerosols. U.S. Energy Research & Development Administration. T10-26608. 1976.

6. Harris, D.B. Procedures for Cascade Impactor Calibration and Operation in Process Streams. EPA-600/2-77-004.

7. Operating Instructions for Andersen Stack Sampling Equipment.

APPENDIX A

TEST SCHEDULE AND PLANT PRODUCTION RATE

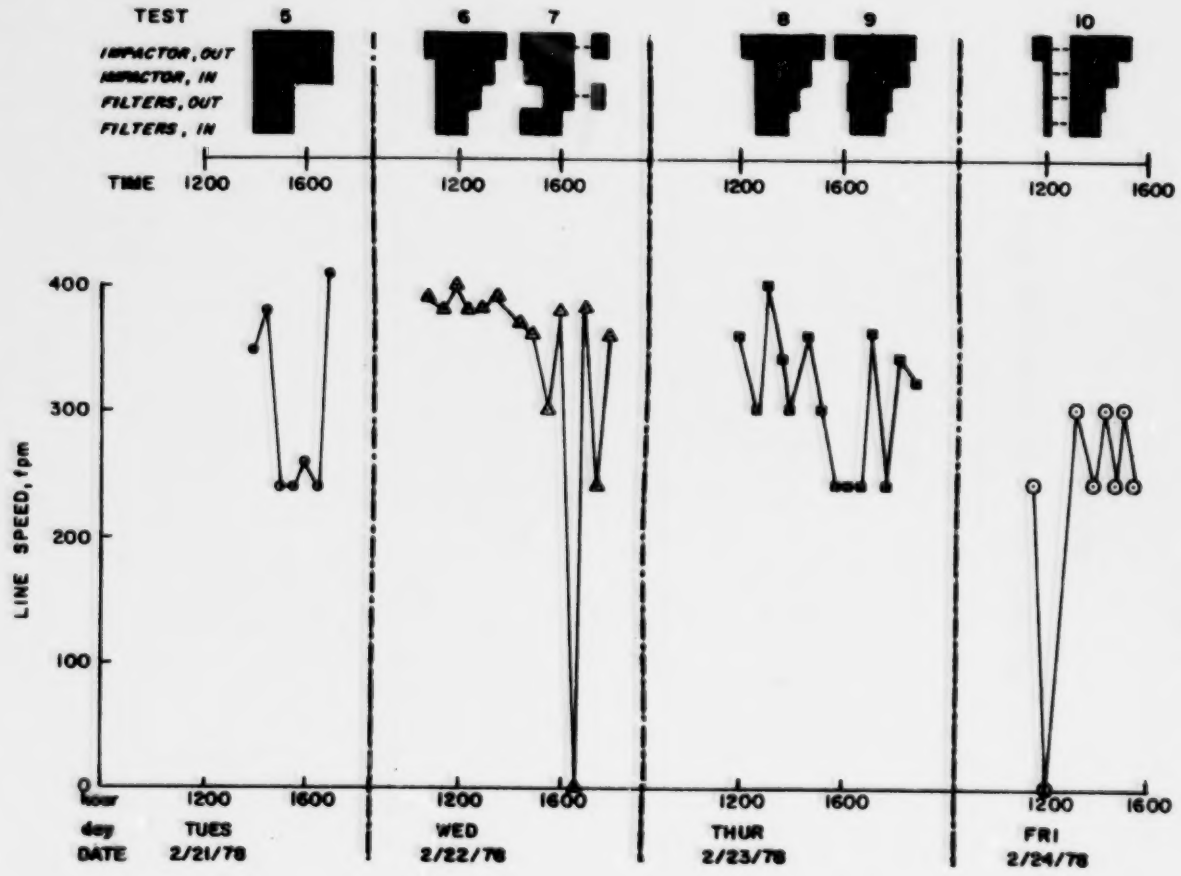

Figure A-1. Test schedule and plant production rate

APPENDIX B

COMPARATIVE SIZE DISTRIBUTIONS FOR TESTS ON EFB UNIT

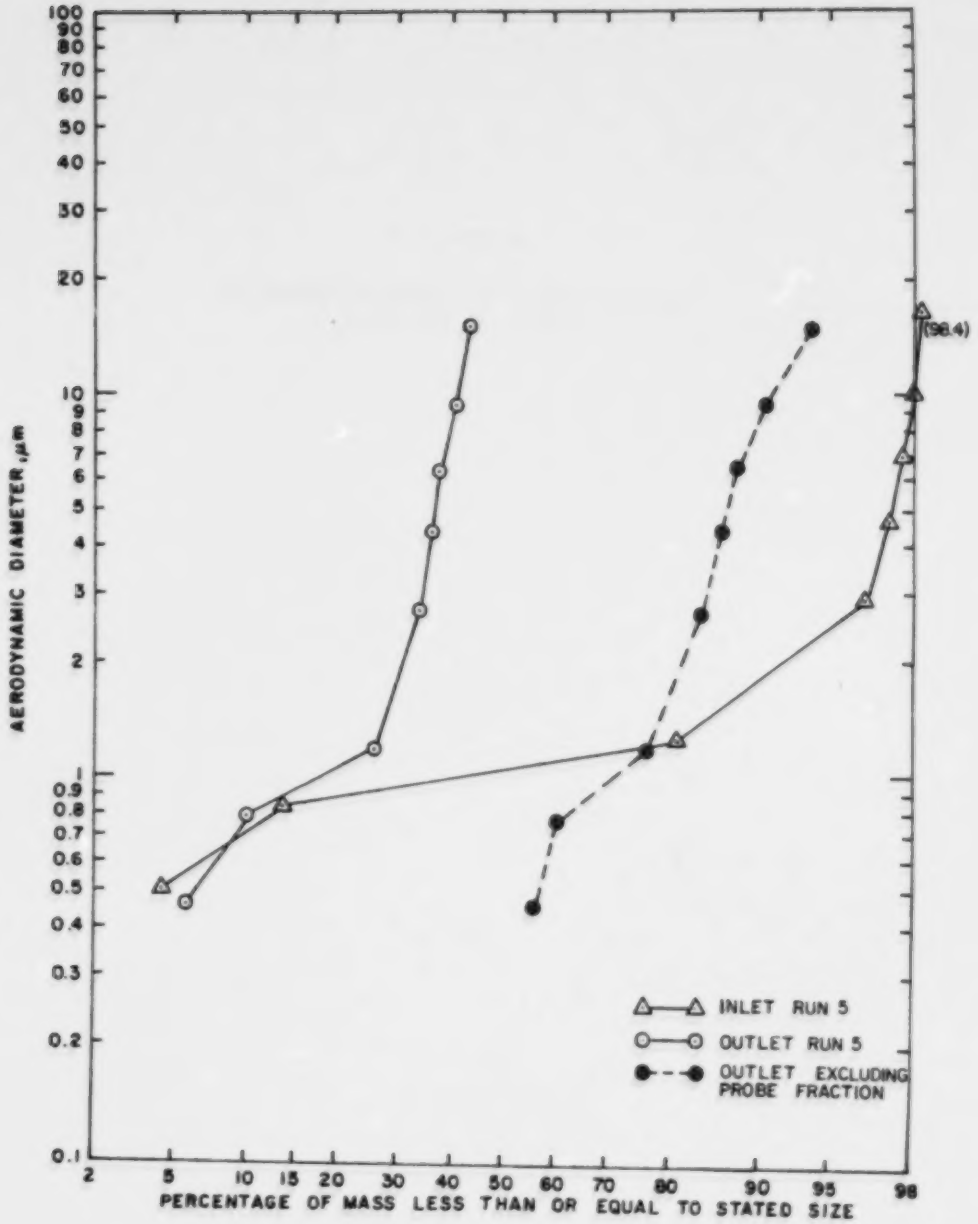
AERODYNAMIC DIAMETER, µm
PERCENTAGE OF MASS LESS THAN OR EQUAL TO STATED SIZE
(98.4)
INLET RUN 5
OUTLET RUN 5
OUTLET EXCLUDING PROBE FRACTION

Figure B-1. Results of run No. 5

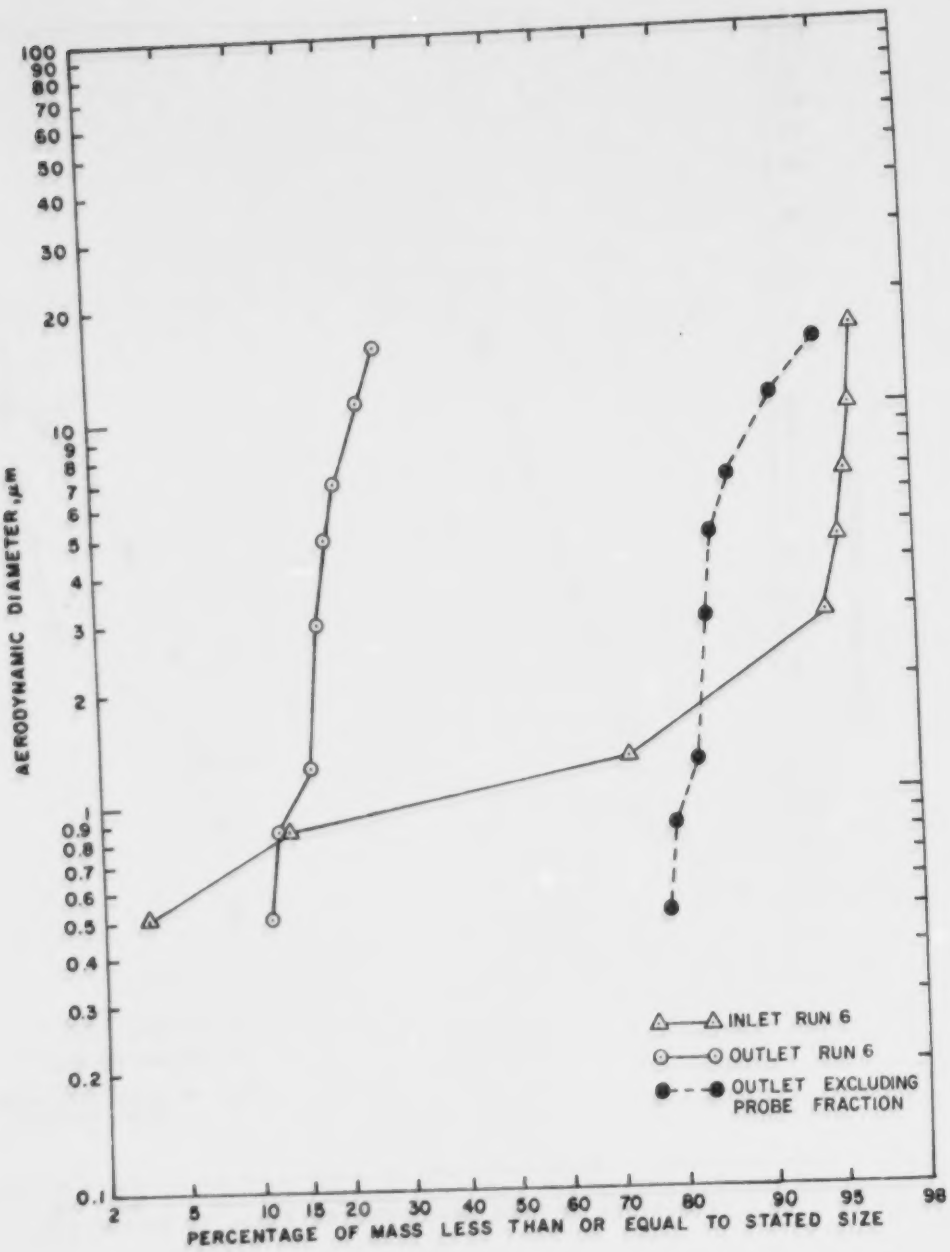

Figure B-2. Results of run No. 6

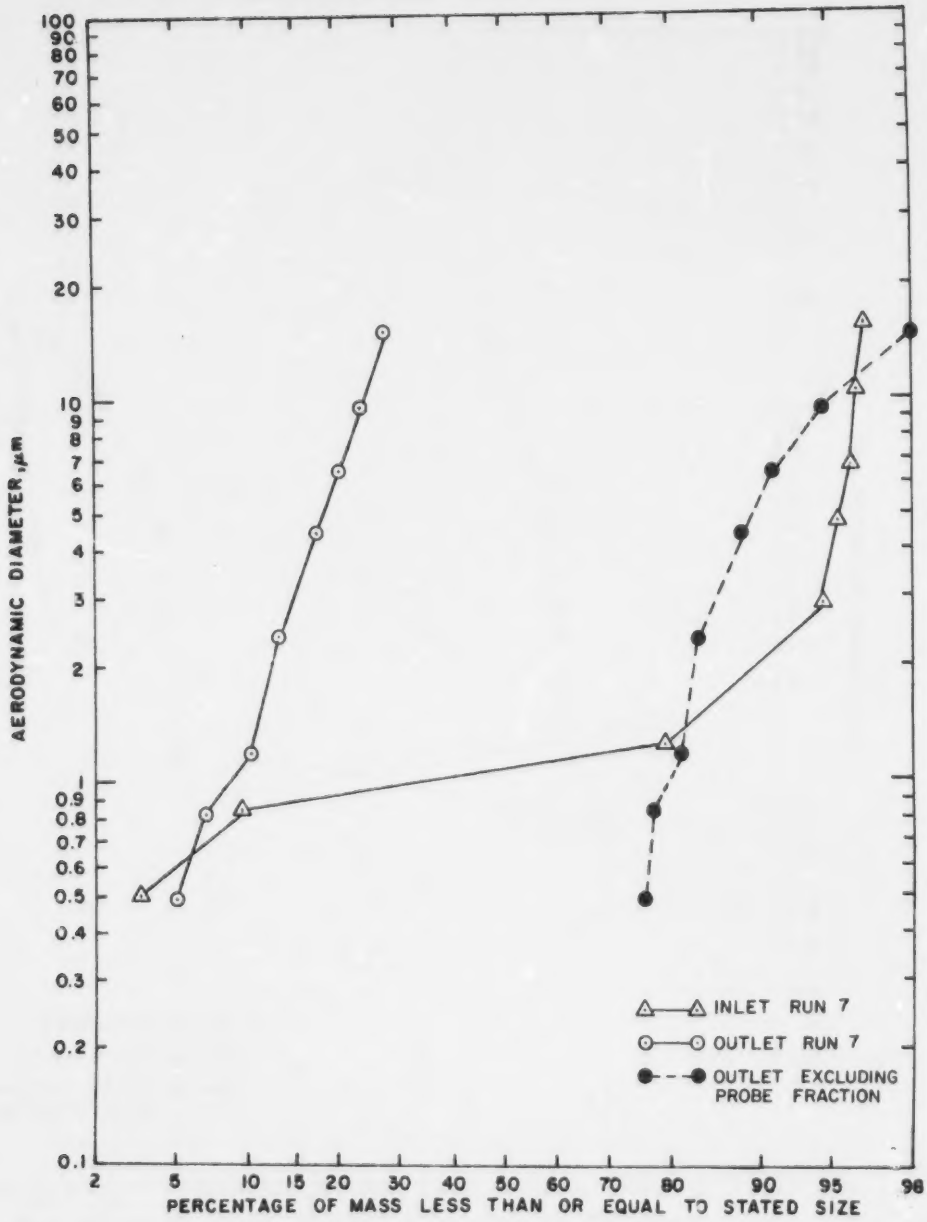

Figure B-3. Results of run No. 7

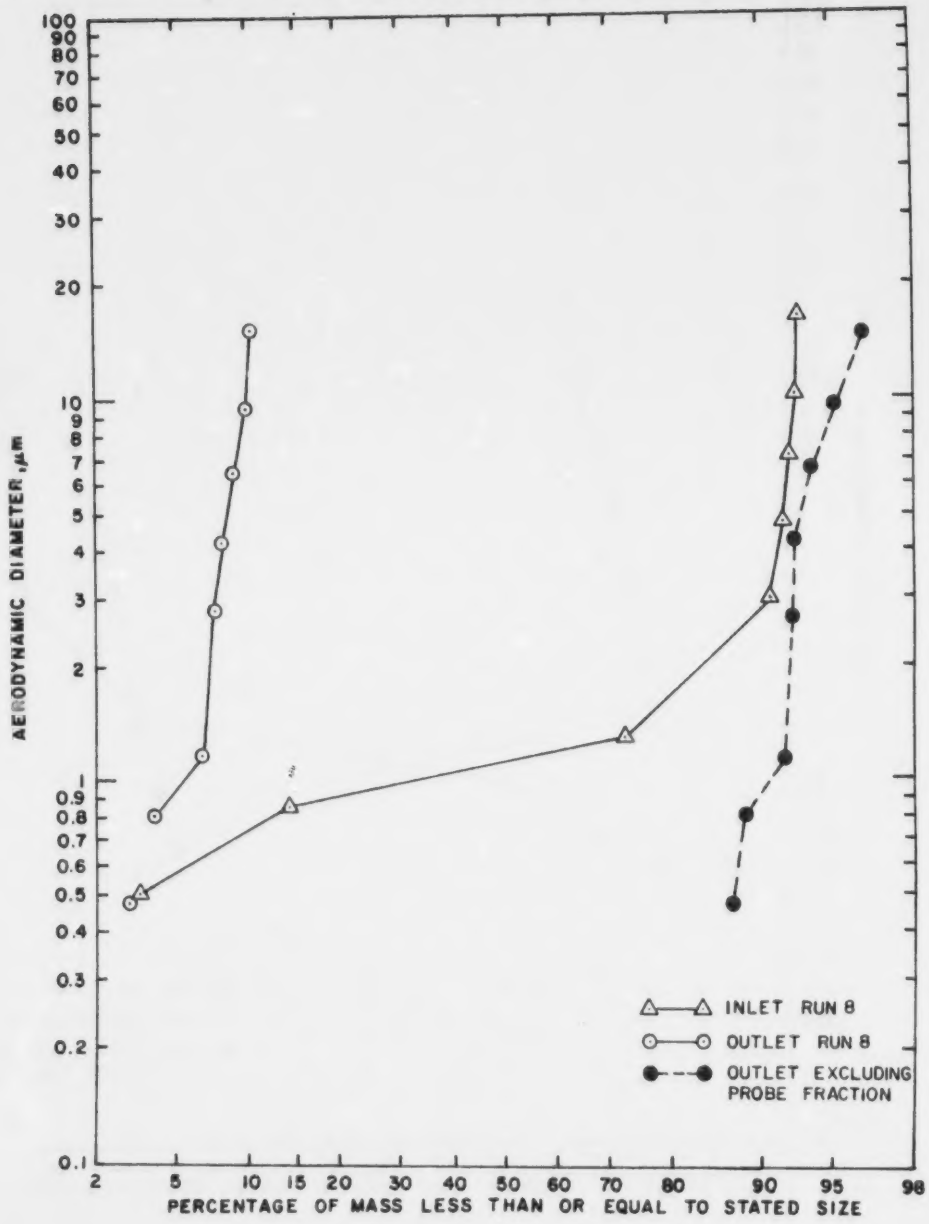

Figure B-4. Results of run No. 8

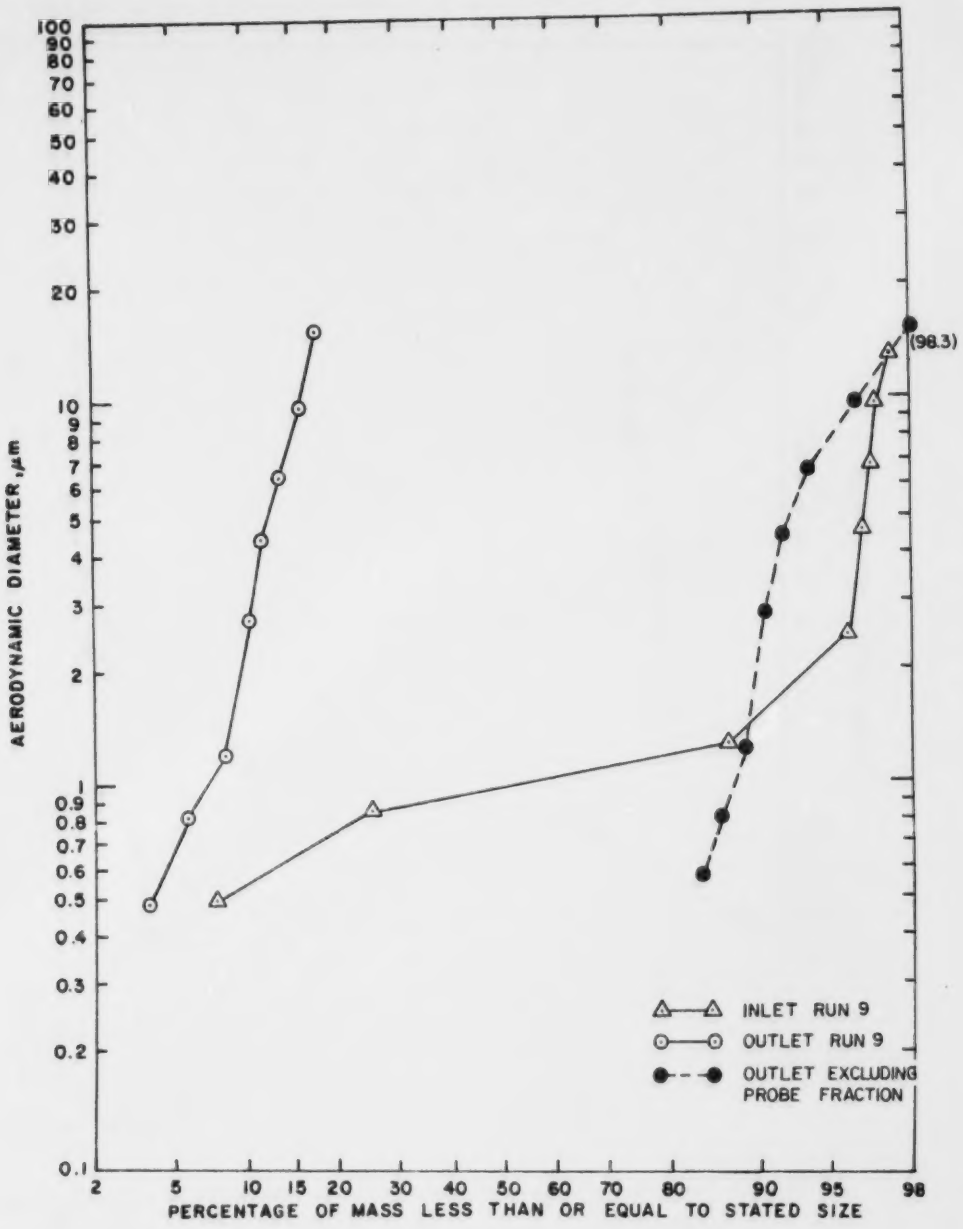

Figure B-5. Results of run No. 9

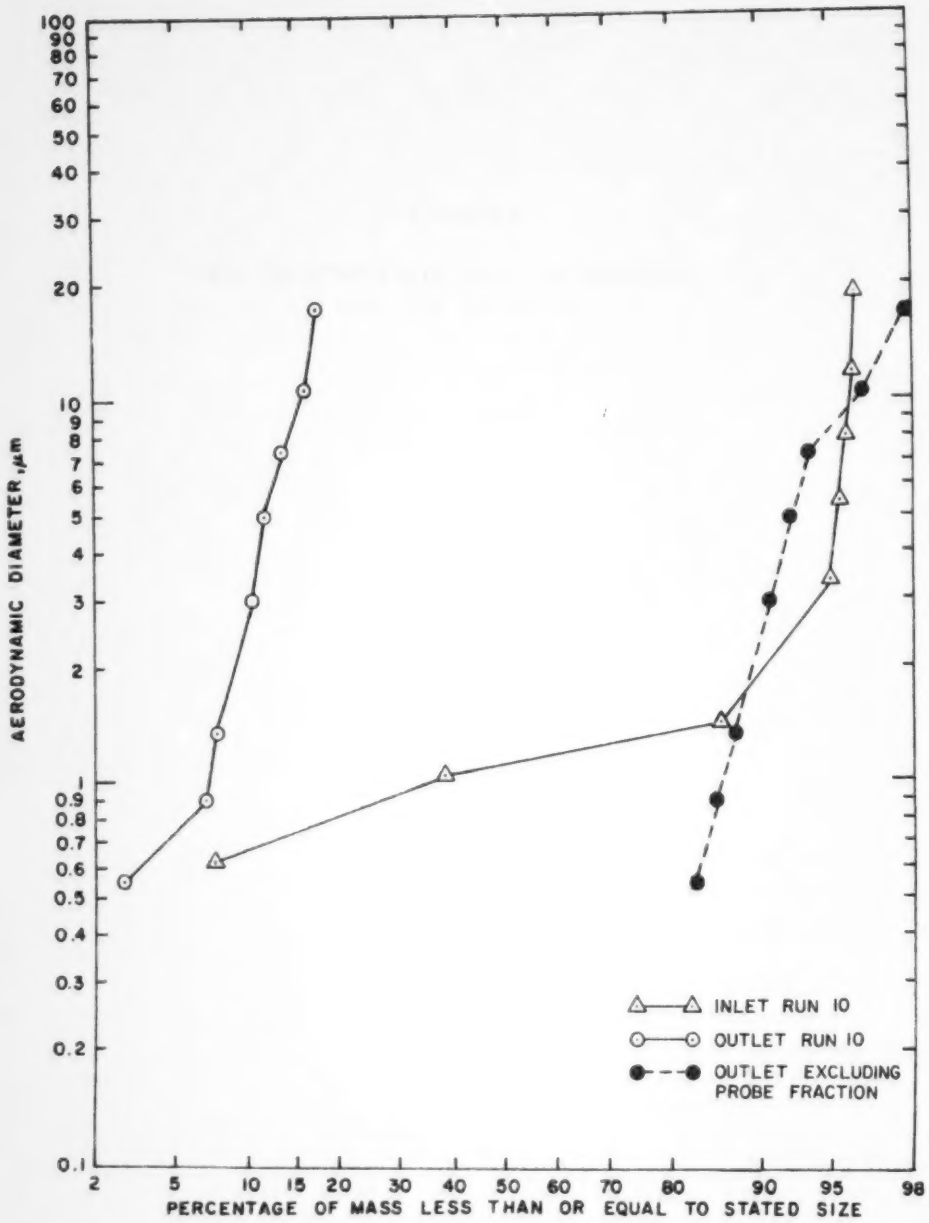

Figure B-6. Results of run No. 10

APPENDIX C

DIFFERENTIAL SIZE DISTRIBUTIONS FOR TESTS ON EFB UNIT

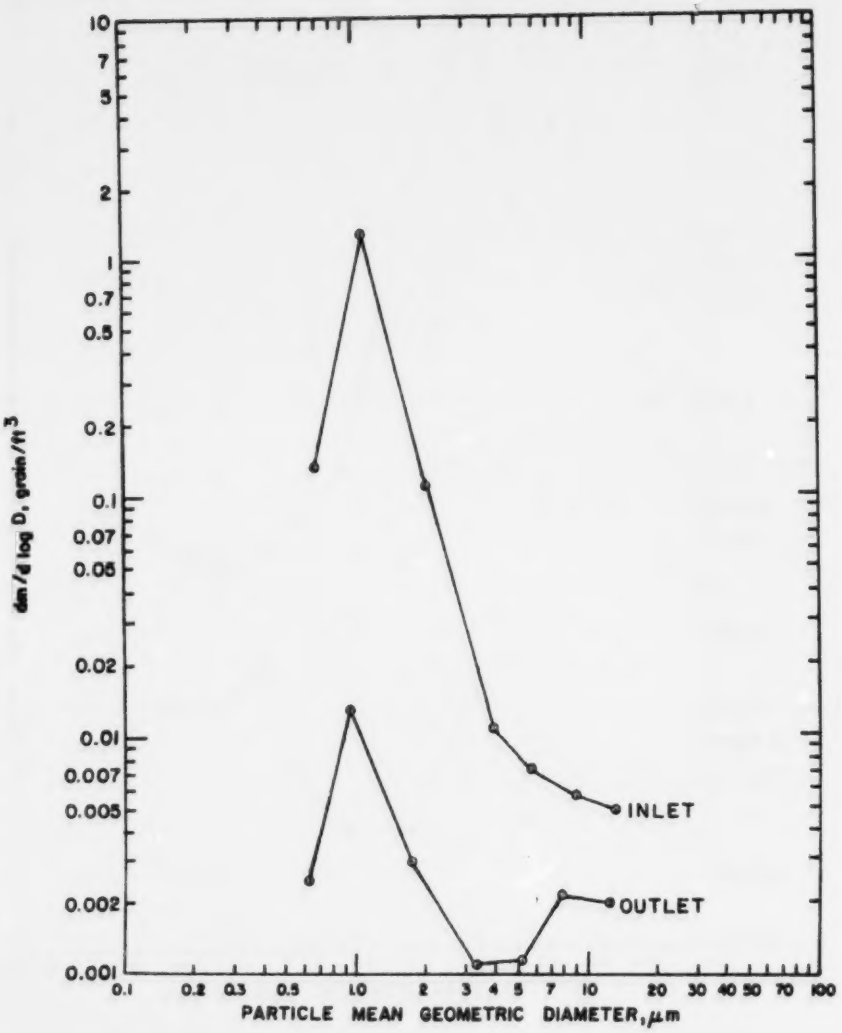

Figure C-1. Results of run No. 5

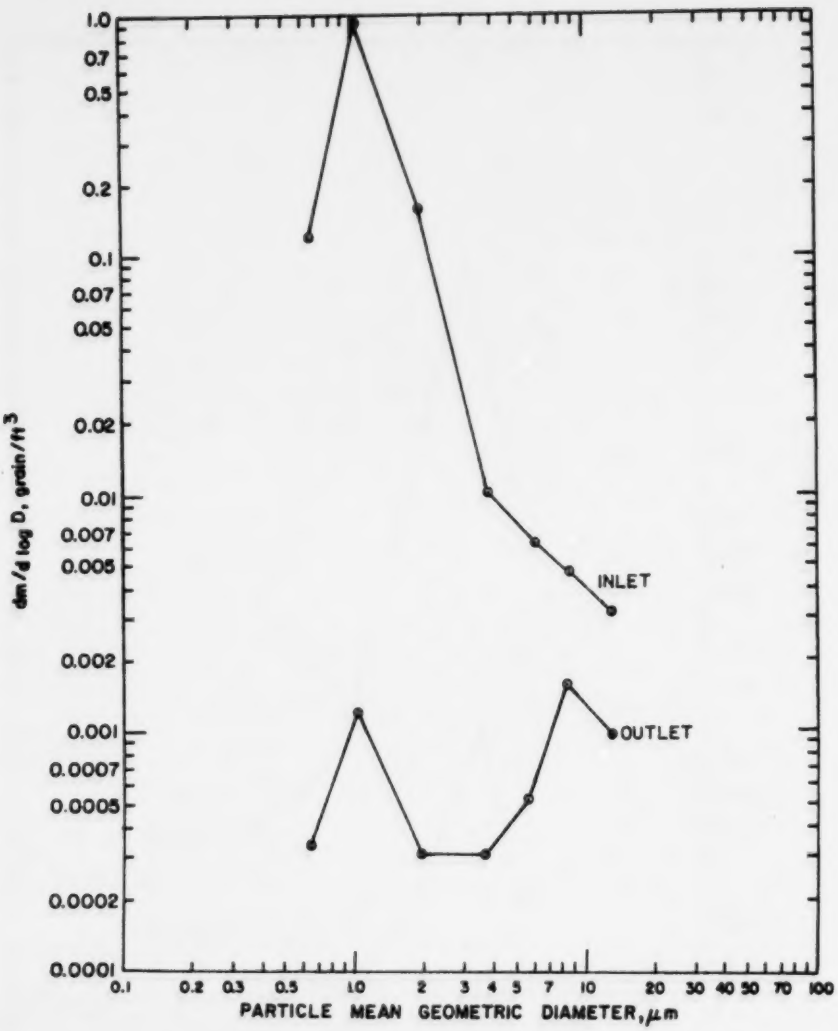

Figure C-2. Results of run No. 6

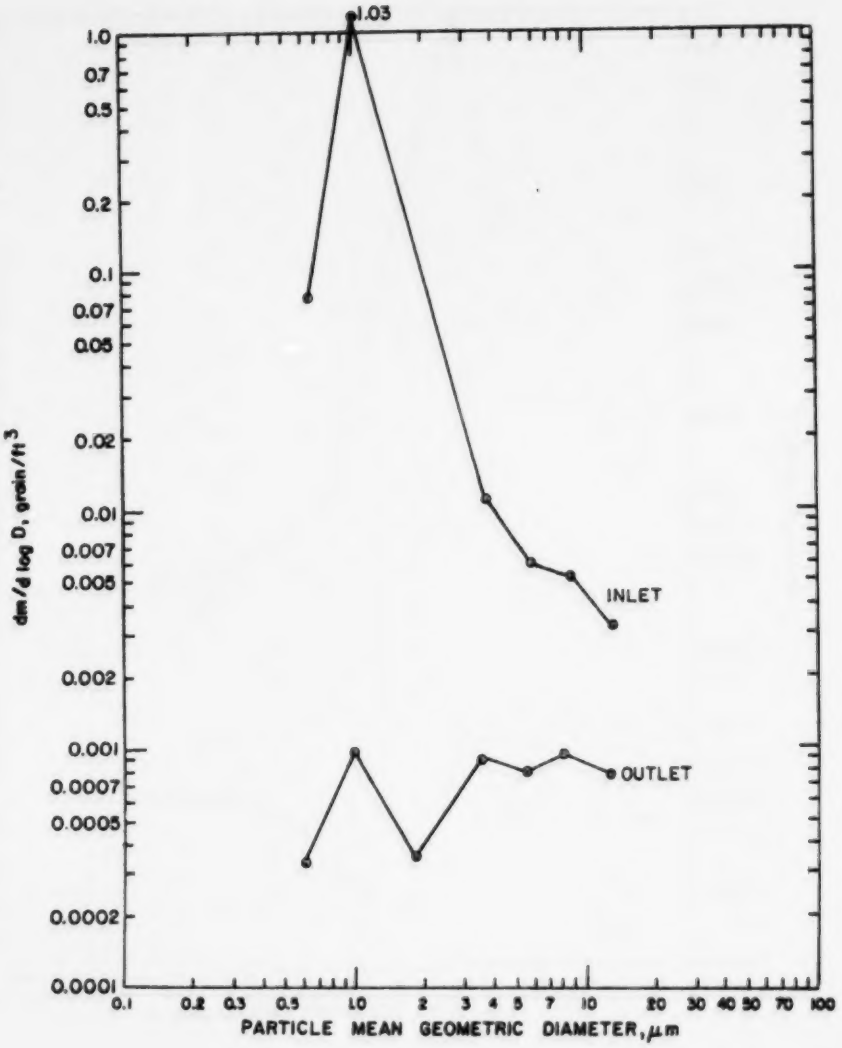

Figure C-3. Results of run No. 7

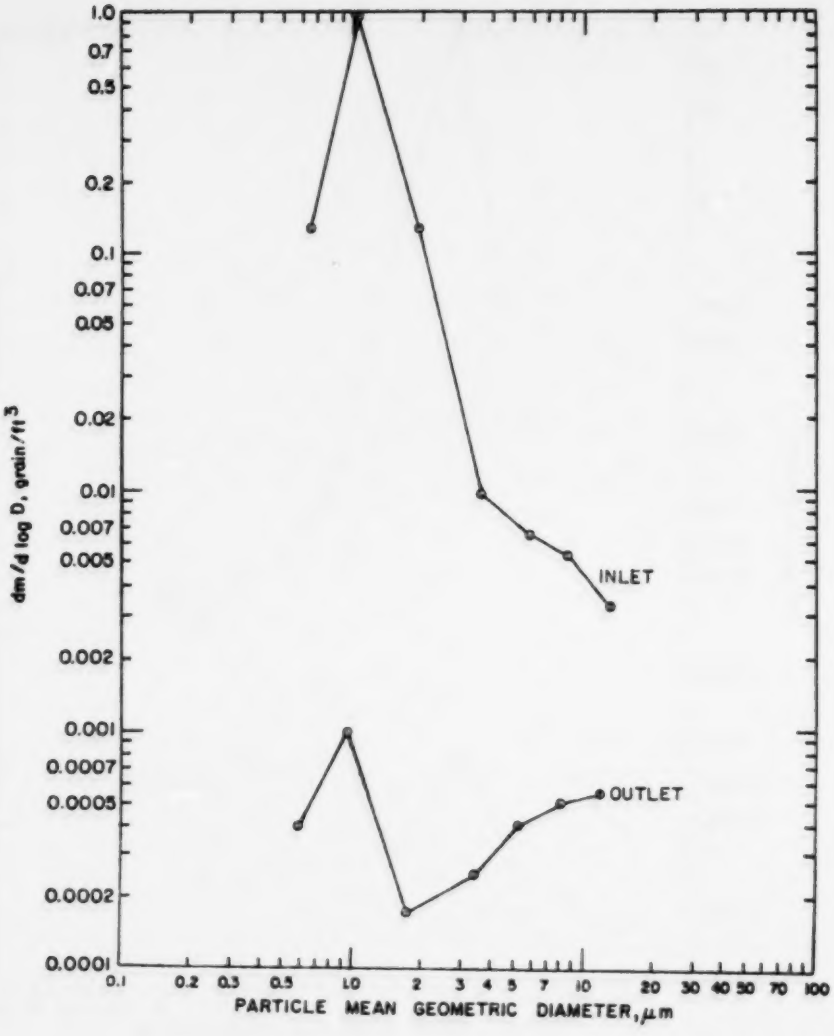

Figure C-4. Results of run No. 8

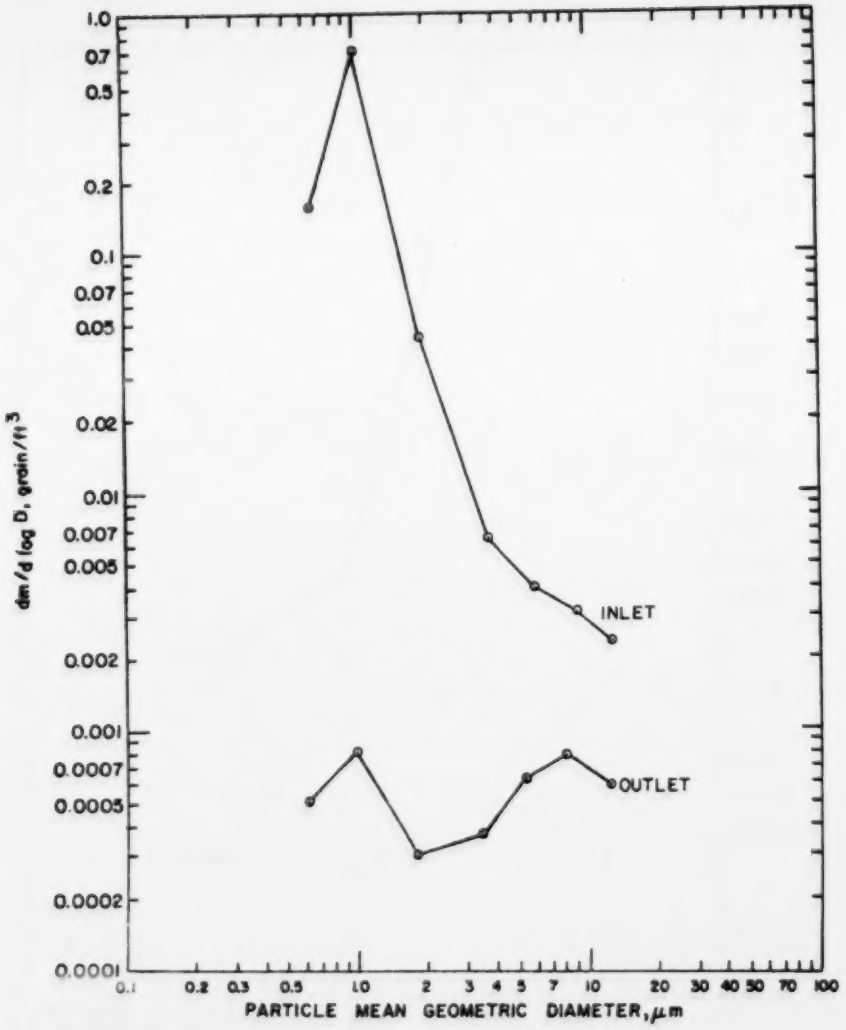

Figure C-5. Results of run No. 9

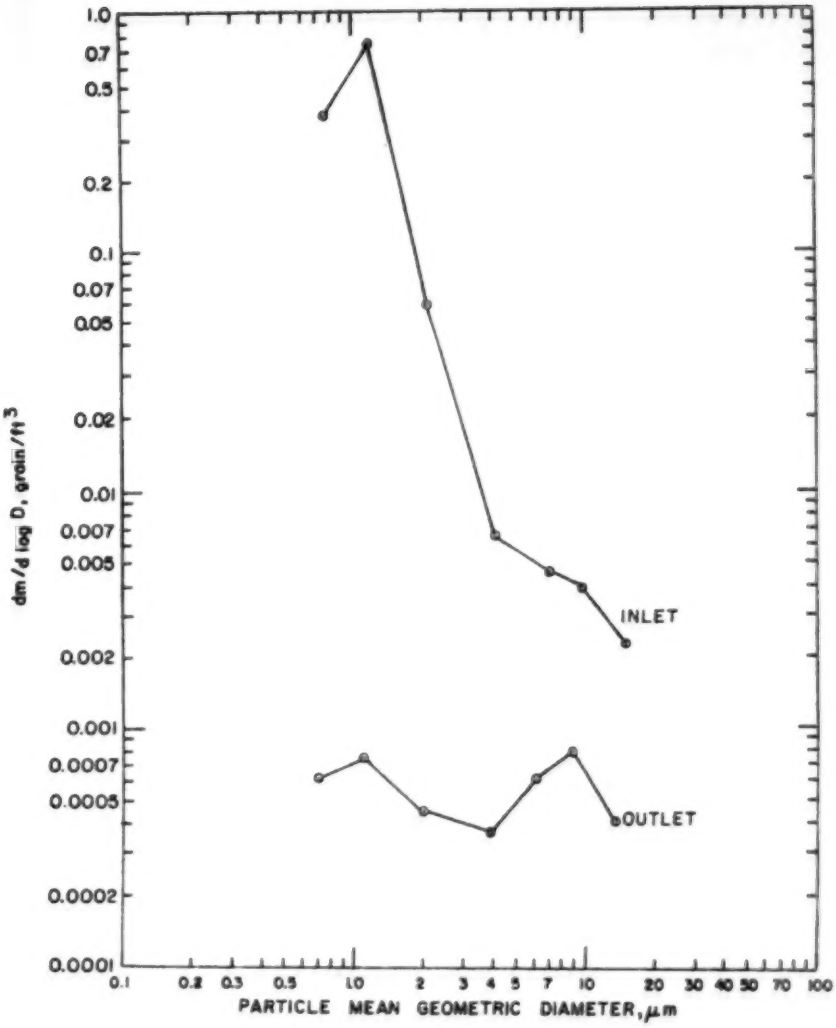

Figure C-6. Results of run No. 10

APPENDIX D

CALCULATOR INPUT/OUTPUT DATA

ANDERSON IMPACTOR

DATE:	2/21/78	RUN #	5
Vm_{std}	58.1954	Pb	29.86
%M	1.75	MW	28.62
Concentration (grains/ft^3)	0.3243	Avg. Pm (-"Hg)	1.4
Qa	0.3658	Avg. Tm (^oF)	76.4
Location	Inlet	H_2O (grams)	21.6
Time	14:00-17:00	Vm	60.846
	9.I = 109.8	Avg. Ps (+"H_2O)	- 0.02
		Avg. To (^oF)	139.4
		TT (min)	180

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% ≤ Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.61631	1.36	—	98.64	—	—
0	0.00292	0.24	16.23	98.40	—	—
1	0.00371	0.31	10.17	98.09	0.0049	12.85
2	0.00356	0.30	6.91	97.79	0.0057	8.39
3	0.00444	0.37	4.72	97.42	0.0072	5.71
4	0.00898	0.75	2.92	96.68	0.0116	3.71
5	0.18744	85.6	1.26	81.08	0.1391	1.92
6	0.80975	67.4	0.85	13.68	1.2830	1.04
7	0.11147	9.28	0.51	4.41	0.1329	0.66
F	0.05293	4.41	—	—		—
TOTAL	1.20151					

ANDERSON IMPACTOR

DATE: 2/21/78 RUN # 5

Vm_{std} 69.4867 Pb 29.86

%M 1.50 MW 28.84

Concentration (grains/ft^3) 0.0131 Avg. Pm (-"H_2) 0.4

Qa 0.4163 (acfm) Avg. Tm (^oF) 72.4

Location Outlet H_2O (grams) 22.0

Time 13:56 - 16:56 Vm 69.845

%I = 114.8 Avg. Ps (+"H_2O) -0.8

Avg. Ts (^oF) 112.0

TT (min) 180.0

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% ≤ Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.02975	50.51	—	49.49	—	—
0	0.00353	6.05	14.95	43.44	—	—
1	0.00178	3.05	9.36	40.39	0.00197	11.83
2	0.00160	2.74	6.37	37.64	0.00216	7.72
3	0.00099	1.70	4.34	35.95	0.00134	5.26
4	0.00096	1.65	2.69	34.30	0.00104	3.41
5	0.00469	8.04	1.16	26.27	0.00290	1.77
6	0.00960	16.46	0.78	9.79	0.01267	0.95
7	0.00246	4.21	0.46	5.57	0.00244	0.60
F	0.00325	5.57	—	—	—	—
TOTAL	0.05831					

ANDERSON IMPACTOR

DATE: 2/22/78 RUN # 6

Vm_{std} 37.8284 Pb 29.64

%M 1.21 MW 28.67

Concentration (grains/ft^3) 0.2698 Avg. Pm (-"Hg) 1.40

Qa 0.3563 (acfm) Avg. Tm (^oF) 75.0

Location Inlet H_2O (grams) 9.70

Time 11:20 - 13:20 Vm 39.9750

%I = 106.0 Avg. Ps (+"H_2O) 0

Avg. Ts (^oF) 134

TT (min) 120

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% < Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.02217	3.39	—	96.61	—	—
0	0.00150	0.23	16.40	96.38	—	—
1	0.00157	0.24	10.27	96.14	0.00389	13.00
2	0.00188	0.29	6.99	95.85	0.00464	8.47
3	0.00251	0.38	4.77	95.47	0.00623	5.77
4	0.00527	0.81	2.95	94.66	0.01045	3.75
5	0.14247	21.80	1.28	72.86	0.16193	1.94
6	0.38530	58.96	0.86	13.89	0.93571	1.05
7	0.06702	10.26	0.51	3.64	0.12260	0.67
F	0.02376	3.64	—	—	—	—
TOTAL	0.65345					

ANDERSON IMPACTOR

DATE: 2/22/78 RUN # 6

Vm_{std} 59.2283 Pb 29.64

%M 1.94 MW 28.59

Concentration (grains/ft^3) 0.0062 Avg. Pm (-"Hg) 0.4

Qa 0.3570 Avg. Tm (°F) 72

Location Outlet H_2O (grams) 24.3

Time 14:30 - 17:43 (cutoff: 13 min) Vm 59.667

%I = 92.3 Avg. Ps (+"H_2O) -0.6

Avg. Ts (°F) 111

TT (min) 180

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% < Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.01550	66.78	—	3322	—	—
0	0.00125	5.39	16.14	27.83	—	—
1	0.00074	3.19	10.88	24.64	0.00097	12.78
2	0.00098	4.22	6.88	20.42	0.00156	8.34
3	0.00032	1.38	4.69	19.04	0.00051	5.68
4	0.00023	0.99	2.91	18.05	0.00029	3.69
5	0.00042	1.81	1.26	16.24	0.00031	1.91
6	0.00078	3.36	0.83	12.88	0.00122	1.04
7	0.00028	1.21	0.51	11.68	0.00033	0.66
F	0.00271	11.68	—	—	—	—
TOTAL	0.02321					

ANDERSON IMPACTOR

DATE: 2/22/78 RUN # 7

Vm_{std} 36.4452 Pb 29.64

%M 1.64 MW 28.63

Concentration (grains/ft^3) 0.2730 Avg. Pm (-"Hg) 1.4

Qa 0.3686 Avg. Tm (°F) 77

Location Inlet H_2O (grams) 12.6

Time 14:45 - 16:36 Vm 38.4920

%I 111.4 Avg. Ps (+"H_2O) 0

Avg. Ts (°F) 134

TT (min) 111.8

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% ≤ Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.01987	3.13	—	96.87	—	—
0	0.00162	0.26	16.12	96.61	—	—
1	0.00154	0.24	10.10	96.37	0.00326	12.76
2	000211	0.33	6.87	96.04	0.00543	8.33
3	0.00236	0.37	4.68	95.66	0.00610	5.67
4	0.00526	0.83	2.90	94.84	0.01086	3.68
5	0.09739	15.35	1.25	79.48	0.11528	1.91
6	0.44297	69.84	0.85	9.65	1.11962	1.03
7	0.03898	6.15	0.50	3.50	0.07413	0.65
F	0.02220	3.50	—	—	—	—
TOTAL	0.63430					

ANDERSON IMPACTOR

DATE: 2/22/71 RUN # 7

Vm_{std} 53.7596 Pb 29.64

%M 1.52 MW 28.64

Concentration (grains/ft^3) 0.0046 Avg. Pm (-"Hg) 0.4

Qa 0.3809 Avg. Tm (°F) 73

Location Outlet H_2O (grams) 17.3

Time 15.24 - 17.40 Vm 54.4911

%I = 97.9 % Avg. Ps (+"H_2O) ~~1.0~~ -0.6

Avg. Ts (°F) ~~10~~ 104

TT (min) 151

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% ∠Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.01118	71.03	—	28.97	—	—
0	0.00028	1.78	15.56	27.19	—	—
1	0.00055	3.49	9.74	23.70	0.00079	12.31
2	0.00054	3.43	6.63	20.27	0.00094	8.04
3	0.00046	2.92	4.52	17.34	0.00081	5.47
4	0.00065	~~4.13~~	2.80	13.21	0.00091	3.56
5	0.00044	2.80	1.21	10.42	0.00035	1.84
6	0.00056	3.56	0.82	6.86	0.00096	1.00
7	0.00026	1.65	0.44	5.21	0.00034	0.63
F	0.00082	5.21	—	—	—	—
TOTAL	0.01574					

ANDERSON IMPACTOR

DATE: 2/23/78

RUN # 8

Vm_{std} 67.0344

Pb 29.60

%M 1.11

MW 28.68

Concentration (grains/ft^3) 0.0074

Avg. Pm (-"Hg) 0.47

Qa 0.4054

Avg. Tm (°F) 75.0

Location Outlet

H_2O (grams) 15.6

Time 12:10 - 15:10

Vm 68.7520

%I = 100.5

Avg. Ps (+"H_2O) -0.5

Avg. Ts (°F) 112.0

TT (min) 180

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% < Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.02685	85.00	—	15.00	—	—
0	0.00106	3.35	15.15	11.65	—	—
1	0.00048	1.52	9.49	10.13	0.00055	11.99
2	0.00035	1.11	6.46	9.02	0.00049	7.83
3	0.00029	0.92	4.40	8.10	0.00040	5.33
4	0.00022	0.70	2.72	7.41	0.00025	3.46
5	0.00027	0.85	1.18	6.55	0.00017	1.79
6	0.00071	2.25	0.80	4.31	0.00097	0.97
7	0.00039	1.23	0.47	3.07	0.00040	0.61
F	0.00097	3.07	—	—	—	—
TOTAL	0.03159					

ANDERSON IMPACTOR

DATE: 2/27/78 RUN # 8

Vm_{std} 37.2506 Pb 29.60

%M 2.04 MW 28.59

Concentration (grains/ft^3) 0.27735 Avg. Pm (-"Hg) 1.35

Qa 0.3355 Avg. Tm (^oF) 79.0

Location Inlet H_2O (grams) 16.1

Time 12:40 - 14:40 Vm 39.3110

%I = 108.6 Avg. Ps (+"H_2O) 0

Avg. Ts (^oF) 141

TT (min) 120

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% < Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.04220	6.43	—	98.57	—	—
0	0.00183	0.28	16.49	93.29	—	—
1	0.00163	0.23	10.33	93.04	0.00339	13.05
2	0.00216	0.33	7.03	92.71	0.60546	8.52
3	0.00230	0.35	4.79	92.36	0.00584	5.81
4	0.00472	0.72	2.97	91.64	0.00958	3.77
5	0.11724	17.88	1.28	73.76	0.13640	1.95
6	0.38939	59.37	0.87	14.39	0.96770	1.06
7	0.07157	10.91	0.52	3.48	0.13392	0.67
F	0.02284	3.48	—	—	—	—
TOTAL	0.65588					

ANDERSON IMPACTOR

DATE:	2/23/78	RUN #	9
Vm_{std}	65.35535	Pb	29.60
%M	1.49	MW	28.64
Concentration (grains/ft^3)	0.00580	Avg. Pm (-"Hg)	0.45
Qa	0.3945	Avg. Tm (^oF)	74.0
Location	Outlet	H_2O (grams)	20.6
Time	15:45-18:45	Vm	66.5950
%I = 96.2		Avg. Ps (+"H_2O)	-0.5
		Avg. Ts (^oF)	111.0
		TT	180

STACE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% ∠Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.01955	80.75	—	19.25	—	—
C	0.60041	1.69	15.33	17.55	—	—
1	0.00050	2.07	9.62	15.49	0.00059	12.15
2	0.00055	2.27	6.54	13.22	0.00078	7.93
3	0.00045	1.86	4.46	11.36	0.00065	5.40
4	0.00032	1.32	2.76	10.04	0.00037	3.51
5	0.00045	1.86	1.19	8.18	0.00030	1.82
6	0.00059	2.44	0.81	5.74	0.00083	0.98
7	0.00048	1.98	0.48	3.76	0.00051	0.62
F	0.00091	3.76	—	—	—	—
TOTAL	0.02421					

ANDERSON IMPACTOR

DATE: 2/23/78 RUN # 9

Vm_{std} 39.6891 Pb 29.60

%M 3.11 MW 28.48

Concentration (grains/ft^3) 0.14620 Avg. Pm (-"Hg) 1.4

Qa 0.3731 Avg. Tm (^oF) 80.0

Location Inlet H_2O (grams) 26.1

Time 16:30 - 18:30 Vm 41.5790

%I = 115.8 Avg. Ps (+"H_2O) 0.0

Avg. Ts (^oF) 132.0

TT (min) 120

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% < Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.01071	2.19	—	97.81	—	—
0	0.00114	0.23	16.00	97.58	—	—
1	0.00118	0.24	10.02	97.34	0.00233	12.67
2	0.00133	0.27	6.82	97.06	0.00319	8.27
3	0.00165	0.34	4.65	96.73	0.00398	5.63
4	0.00338	0.69	2.88	96.03	0.00651	3.67
5	0.04145	8.48	1.25	87.56	0.04573	1.89
6	0.30171	61.70	0.84	25.85	0.71054	1.02
7	0.08883	18.17	0.50	7.69	0.15735	0.65
F	0.03759	7.69	—	—	—	—
TOTAL	0.48897					

ANDERSON IMPACTOR

DATE: 2/24/78 RUN # 10

Vm_{std} 51.7093 Pb ~~29.68~~ ~~29.63~~ 29.64

%M 1.61 MW 28.63

Concentration (grains/ft^3) 0.00557 Avg. Pm (-"Hg) 0.28

Qa 0.3078 Avg. Tm (^oF) 74.0

Location Outlet H_2O (grams) 17.6

Time 11:30 - 15:15 (off 45 min) Vm 52.2500

%I = 118.4 Avg. Ps (+"H_2O) -0.7

Avg. Ts (^oF) 104.0

TT (min) 180

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.01474	80.20	—	19.80	—	—
0	0.00039	2.12	17.31	17.68		
1	0.00028	1.52	10.85	16.16	0.00042	13.71
2	0.00044	2.39	7.39	13.76	0.00080	8.95
3	0.00033	1.79	5.04	11.97	0.00060	6.10
4	0.00025	1.36	3.61	10.61	0.00036	3.97
5	0.00053	2.88	1.36	7.73	0.00044	2.06
6	0.00042	2.29	0.92	5.44	0.00076	1.12
7	0.00045	2.45	0.55	2.99	0.00061	0.71
F	0.00055	2.99	—	—	—	—
TOTAL	0.01838					

ANDERSON IMPACTOR

DATE:	2/24/78	RUN #	10
Vm_{std}	28.3347	Pb	29.64
%M	1.35	MW	28.66
Concentration (grains/ft^3)	0.2658	Avg. Pm (-"Hg)	0.80
Qa	0.2655	Avg. Tm (^oF)	76.0
Location	Inlet	H_2O (grams)	8.10
Time	1200-14:45 (Coff 45 min)	Vm	29.3330
	%I = 102.5	Avg. Ps (+"H_2O)	0.0
		Avg. Ts (^oF)	131.0
		TT (min)	120

STAGE	Net weight (gm)	% On Stage	Size Cutoff (μm)	% < Stated Size	dm/d log D	Geo. Mean (μm)
Probe & Expander	0.01693	3.52	—	96.48	—	—
0	0.00094	0.20	18.98	96.28	—	—
1	0.00085	0.18	15.89	96.11	0.00231	15.02
2	0.00116	0.24	8.90	95.87	0.00384	9.81
3	0.00142	0.29	5.52	95.58	0.00472	6.69
4	0.00250	0.52	3.43	95.06	0.00665	4.35
5	0.04051	8.41	1.49	86.64	0.06197	2.26
6	0.23363	48.53	1.01	38.11	0.76783	1.23
7	0.14810	30.76	0.61	7.35	0.36950	0.79
F	0.03539	7.35	—	—	—	—
TOTAL	0.48143					

APPENDIX E

IMPACTOR DATA CALIBRATION AND CONVERSIONS

Particle diameters reported are calculated according to the method described by Seymour Calvert, Charles Lake, and Richard Parker, 1976, Cascade Impactor Calibration Guidelines, EPA, IERL, EPA-600/2-76-118.

The results thus reported represent the "aerodynamic impaction diameters." These particle diameters can be related to the classical aerodynamic diameters by $D_a = D_i \left(\frac{1}{C_{Da}}\right)^{\frac{1}{2}}$ where C_{Da} is the Cunningham slip factor for the aerodynamic diameter. The impaction diameter may also be calculated as the Stokes' diameter by

$$D_s = D_i \left(\frac{1}{C_{Ds}\ p}\right)^{\frac{1}{2}}$$

where C_{Ds} is the corresponding Cunningham slip factor for a particle of the Stokes diameter D_s and p is the particle density (approximately equal to No. 6 oil).

These calculations may be approximated by trial fittings or may be calculated by a computer program. Table E-1 contains the results of a computer computation of the equivalent diameters. These results are based on the assumed particle density of 0.99 g/cm^3. This data was provided by Midwest Research Institute, Kansas City, Missouri.

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TABLE E-1. EQUIVALENT AERODYNAMIC DIAMETERS FOR TESTS 5 THROUGH 10

TEST NO. 5 IN

STOKES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC IMPACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
14.749		14.725		14.456	
9.438	11.644	9.192	11.414	9.365	11.244
5.854	7.604	5.727	7.466	5.678	7.324
4.041	5.156	4.018	5.126	4.341	5.259
2.595	3.418	2.582	3.301	2.686	3.415
1.667	1.676	1.676	1.667	1.161	1.766
.710	.877	.706	.872	.784	.954
.447	.561	.456	.529	.494	.603

TEST NO. 5 OUT

STOKES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC IMPACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
16.074		14.493		14.245	
10.038	12.712	9.988	12.638	11.144	12.444
5.805	7.355	5.771	7.273	6.419	8.648
4.014	5.083	4.048	5.045	4.716	5.712
2.867	3.612	2.812	3.593	2.919	3.710
1.183	1.829	1.177	1.819	1.263	1.920
.778	.959	.774	.954	.853	1.038
.494	.585	.437	.581	.507	.658

TEST NO. 6 IN

STOKES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC IMPACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
16.241		16.155		15.900	
10.141	12.832	10.090	12.767	10.272	12.474
5.878	8.358	5.841	8.308	6.468	8.474
4.064	5.167	4.044	5.144	4.705	5.771
2.858	3.598	2.843	3.632	2.950	3.749
1.198	1.859	1.192	1.841	1.278	1.962
.789	.972	.788	.967	.864	1.051
.500	.618	.443	.598	.514	.665

TEST NO. 6 OUT

STOKES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC IMPACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
14.984		14.903		14.144	
9.406	12.012	9.433	12.564	10.114	12.774
5.761	8.221	5.736	8.174	6.583	8.448
4.583	5.315	4.567	5.546	4.645	5.683
2.814	3.544	2.800	3.576	2.906	3.693
1.181	1.823	1.175	1.814	1.261	1.914
.778	.959	.774	.962	.853	1.037
.494	.585	.438	.582	.508	.658

TABLE E-1 (continued).

TEST NO. 7 IN

STORES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC INTERACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
14.982		14.982		14.123	
9.464	12.814	9.418	12.551	10.044	12.760
6.151	8.201	6.121	8.154	6.471	8.440
4.382	5.364	4.354	4.438	4.644	5.473
2.807	3.486	2.793	3.568	2.899	3.585
1.179	1.816	1.149	1.807	1.256	1.907
.773	.943	.748	.948	.848	1.832
.445	.580	.433	.537	.525	.643

TEST NO. 7 OUT

STORES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC INTERACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
14.547		14.319		14.555	
9.614	12.187	9.466	12.104	9.744	12.511
6.218	7.916	6.085	7.978	6.518	8.317
4.414	5.387	4.346	5.324	4.528	5.674
2.787	3.458	2.693	3.441	2.745	3.556
1.134	1.752	1.128	1.742	1.213	1.442
.766	.914	.741	.914	.820	.997
.421	.550	.413	.547	.484	.611

TEST NO. 8 IN

STORES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC INTERACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
14.527		14.245		14.648	
10.190	12.983	10.146	12.834	10.324	13.051
6.418	8.147	6.278	8.354	7.028	8.530
4.588	5.845	4.484	5.446	4.741	5.403
2.875	3.670	2.858	3.641	2.964	3.749
1.206	1.860	1.197	1.850	1.284	1.941
.781	.977	.782	.972	.848	1.046
.448	.596	.445	.563	.516	.664

TEST NO. 8 OUT

STORES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC INTERACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
14.468		14.423		15.154	
9.854	11.851	9.717	11.791	9.941	11.964
6.345	7.710	6.211	7.669	6.457	7.978
4.301	5.224	4.279	5.197	4.401	5.481
2.732	3.340	2.619	3.347	2.723	3.452
1.094	1.701	1.093	1.692	1.178	1.741
.721	.890	.717	.845	.798	.984
.435	.593	.434	.537	.473	.611

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TABLE E-1 (continued).

TEST NO. 9 IN

STOKES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC IMPACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
15.844		15.764		16.004	
9.899	12.520	9.844	12.457	10.024	12.668
6.787	8.196	6.671	8.105	6.820	8.264
4.947	5.822	4.924	5.444	4.849	5.631
2.785	3.554	2.771	3.541	2.877	3.657
1.155	1.802	1.159	1.792	1.245	1.893
.766	.946	.742	.940	.841	1.023
.431	.575	.420	.572	.449	.648

TEST NO. 9 OUT

STOKES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC IMPACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
15.195		15.119		15.382	
9.497	12.007	9.439	11.946	9.615	12.169
6.430	7.810	6.397	7.771	6.542	7.931
4.358	5.674	4.336	5.267	4.459	5.401
2.659	3.411	2.655	3.393	2.760	3.508
1.116	1.729	1.110	1.717	1.195	1.816
.733	.904	.729	.899	.807	.982
.412	.549	.410	.546	.479	.622

TEST NO. 10 IN

STOKES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC IMPACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
18.691		18.706		18.976	
11.755	14.865	11.695	14.791	11.944	15.023
7.979	9.655	7.939	9.546	8.099	9.815
5.420	6.576	5.393	6.543	5.527	6.691
3.333	4.250	3.316	4.229	3.428	4.353
1.411	2.164	1.403	2.157	1.443	2.262
.937	1.158	.932	1.144	1.014	1.230
.534	.718	.535	.706	.609	.786

TEST NO. 10 OUT

STOKES-DIA (UM)		CLASSIC AERODYNAMIC DIA (UM)		AERODYNAMIC IMPACTION DIA (UM)	
BNDRY	MID PT	BNDRY	MID PT	BNDRY	MID PT
17.187		17.061		17.314	
10.716	13.555	10.662	13.487	10.850	13.706
7.271	8.797	7.234	8.752	7.387	8.953
4.936	5.971	4.911	5.940	5.060	6.102
3.031	3.858	3.015	3.848	3.124	3.968
1.274	1.964	1.272	1.959	1.360	2.061
.847	1.041	.842	1.035	.923	1.120
.484	.648	.481	.637	.553	.716

CONVERSION FACTORS FOR BRITISH AND METRIC UNITS

To convert from	To	Multiply by	To	Multiply by
^{o}F	^{o}C	$\frac{5}{9}$ (^{o}F-32)	———	———
ft	meters	0.305	centimeters	30.5
ft^2	$meters^2$	0.0929	$centimeters^2$	929.0
ft^3	$meters^3$	0.0283	$centimeters^3$	28,300.0
ft/min (fpm)	centimeters/sec	0.508	meters/sec	5.08×10^{-3}
ft^3/min	$centimeters^3$/sec	471.9	$meters^3$/hr	1.70
in.	centimeters	2.54	meters	2.54×10^{-2}
$in.^2$	$centimeters^2$	6.45	$meters^2$	6.45×10^{-4}
oz	grams	28.34	grains	438.0
oz/yd^2	$grams/meter^2$	33.89	$grams/centimeter^2$	3.39×10^{-3}
grains	grams	0.0647	———	———
$grains/ft^2$	$grams/meter^2$	0.698	———	———
$grains/ft^3$	$grams/meter^3$	2.288	———	———
lb force	dynes	4.44×10^5	Newtons	0.44
lb mass	kilograms	0.454	grams	454.0
lb/ft^2	$grams/centimeter^2$	0.488	$grams/meter^2$	4,880.0
in. H_2O/ft/min	cm H_2O/cm/sec	5.00	$Newtons/meter^2$/cm/sec	490.0
Btu	calories	252	———	———